SM & MSSM CORRECTIONS TO TOP-QUARK HADRO-PRODUCTION IN DOUBLE & SINGLE TOP CHANNELS

(QMUL, 18 MAY 2011)

STEFANO MORETTI

NExT INSTITUTE, UNIV. OF SOUTHAMPTON AND RAL, UK

IN COLLABORATION WITH

MR NOLTEN[†], DA ROSS[†], L PANIZZI[†,*], G MACORINI[†,$] AND M WIEBUSCH[†,#]

[†] SOUTHAMPTON, UK

[*] IPNL LYON, FRANCE

[$] LECCE, ITALY

[#] RWTH AACHEN, GERMANY

DISCLAIMER

- WILL NOT DESCRIBE SM QCD EFFECTS (APART FROM $A_{FB}(t\bar{t})$)
- WILL CONCENTRATE ON: SM EW, MSSM EW & QCD
- ONLY LHC 14 TEV RESULTS

OUTLINE

- WHY EW CORRECTIONS CAN BE IMPORTANT IN HADRONIC PROCESSES
- SM EW EFFECTS IN TOP-QUARKS HADRO-PRODUCTION
- MSSM QCD & EW EFFECTS THEREIN
- SUMMARY

CORRECTIONS TO HADRONIC OBSERVABLES: QCD VS EW

- LARGE SCALE DEPENDENCE OF HIGHER ORDER CORRECTIONS OFTEN DOMINATES THEORETICAL UNCERTAINTIES !

- QCD CORRECTIONS TYPICALLY LARGEST:

$$\alpha_S \approx 10\, \alpha_{EW} \qquad (\alpha_{EW} = \alpha_{EM}/\sin^2\theta_W).$$

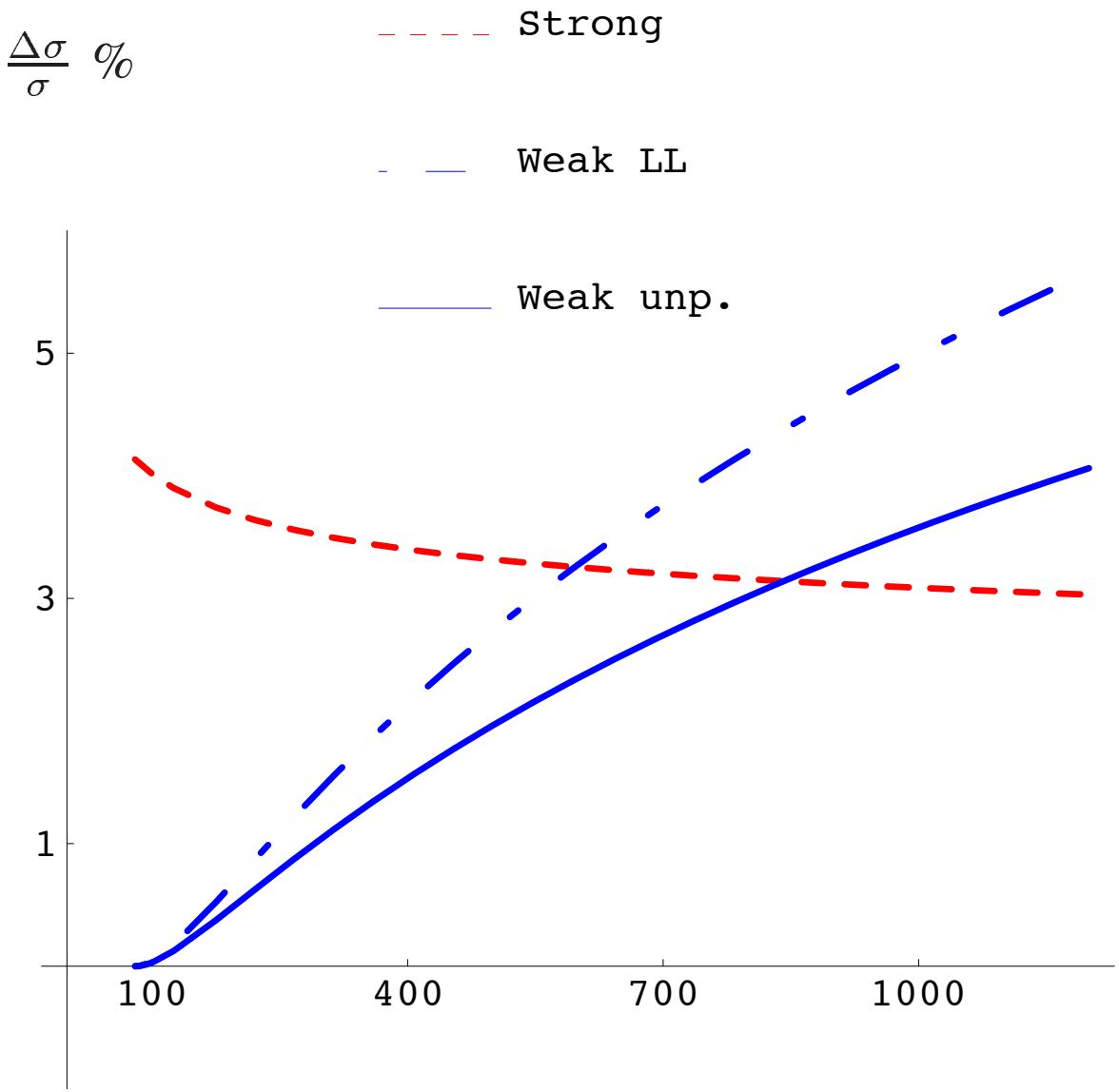
BUT ....

- THERE ARE LARGE LOG AROUND IN EW CASE: AT $\sqrt{s} = 1\,\mathrm{TeV}$

$$\frac{\alpha}{4\pi s_{\mathrm{w}}^2}\log^2\frac{s}{M_{\mathrm{W}}^2} = 6.6\%, \qquad \frac{\alpha}{4\pi s_{\mathrm{w}}^2}\log\frac{s}{M_{\mathrm{W}}^2} = 1.3\%.$$

- NNLO QCD CORRECTIONS WILL SOON BE AVAILABLE: RECALL $\alpha_S^2 \approx \alpha_{EW}$!

- CONSIDER LEPTONIC COLLISIONS: AT HIGH ENERGIES, $\sqrt{s} \gg M_W$ (ILC, 0.5 TO 3 TEV), EW INTERACTIONS BECOME STRONG:



TOTAL (INCLUSIVE) HADRONIC CROSS SECTION

ENERGY (GEV)

SUDAKOV LOGS^2 IN A NUTSHELL

- CORRESPOND TO SOFT AND COLLINEAR SINGULARITIES IN THEORIES WITH MASSLESS BOSONS, WHERE THEY ARE CANCELED BY REAL RADIATION.

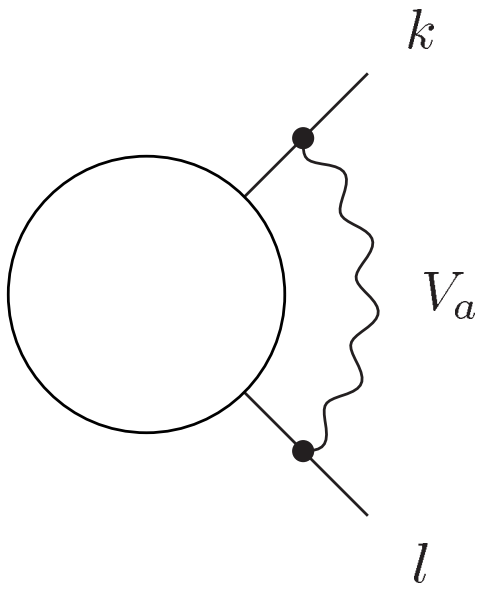
- REGULATED BY BOSON MASS IN EW CASE: THEY ARE FINITE !

  PHYSICAL DEPENDENCE ON IR CUT-OFF M_W REMAINS

- IN FEYNMAN GAUGE THEY ARE ASSOCIATED WITH VIRTUAL GRAPHS WHERE SOFT-COLLINEAR BOSONS ARE EXCHANGED BETWEEN EXTERNAL LEGS. (IN AXIAL GAUGE THEY ARE ASSOCIATED WITH SELF ENERGY GRAPHS ON EXTERNAL LEGS.)

- DL ARE UNIVERSAL: ONLY DEPEND ON EXTERNAL PARTICLES !

$$\sum_{k=1}^{n}\sum_{l<k}\sum_{V_a=\mathrm{A,Z,W}^{\pm}}$$

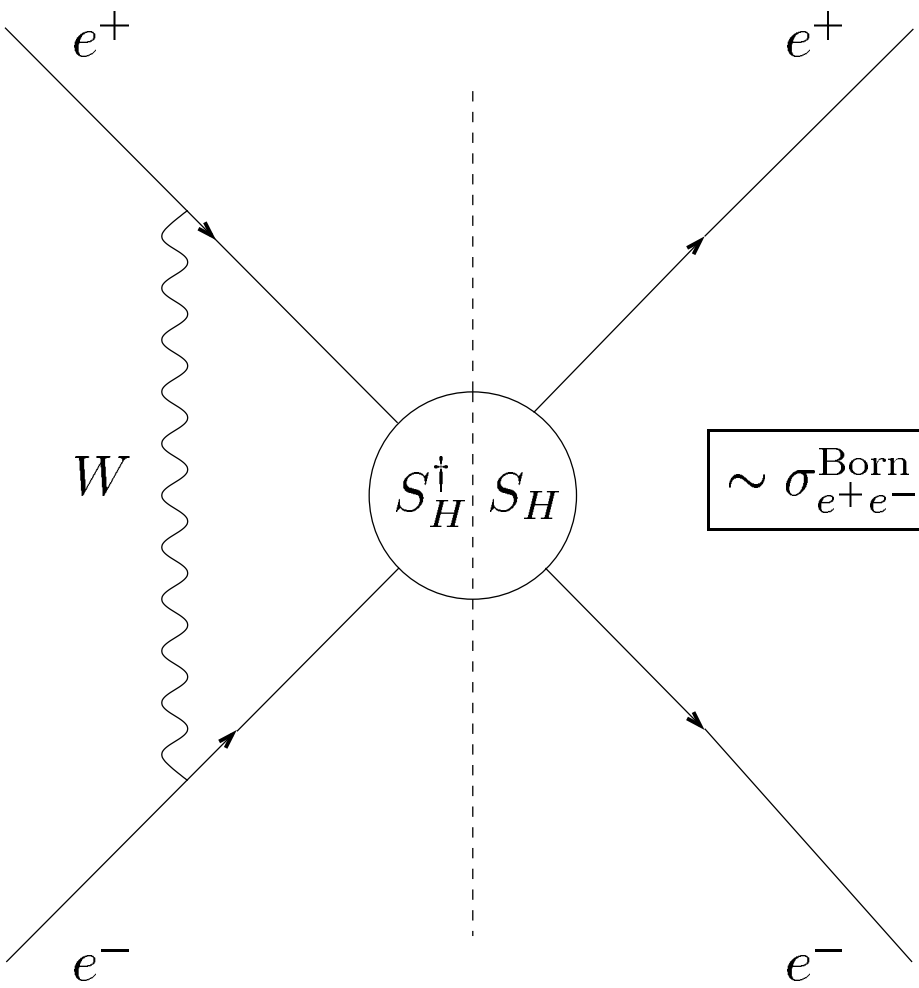


$$= \sum_{k=1}^{n}\sum_{l<k}\sum_{V_a=\mathrm{A,Z,W}^{\pm}} \alpha/4\pi \log^2(r_{kl}/M^2) T_{kl}$$

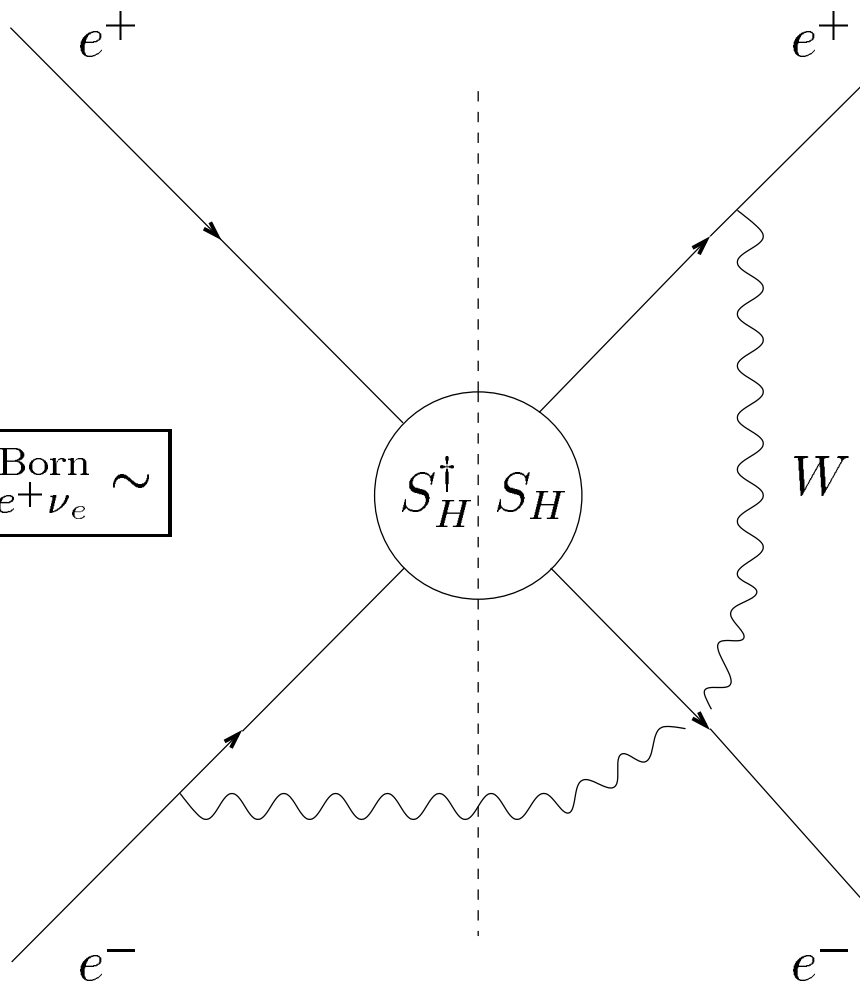
$$\log^2 \frac{r_{kl}}{M^2} = \log^2 \frac{s}{M^2} + 2\log \frac{s}{M^2} \log \frac{r_{kl}}{s} + \log^2 \frac{r_{kl}}{s} \qquad r_{kl} = (p_k \pm p_l)^2$$

- NUMERICALLY AT TeV ENERGIES THERE ARE LARGE CANCELLATIONS BETWEEN DOUBLE LOG (DL) AND SINGLE LOG (SL) CONTRIBUTIONS.

- DL (AND SL) DO NOT CANCEL IN INCLUSIVE MEASUREMENTS (AKA VIOLATION OF BLOCH-NORDSIECK THEOREM IN NON-ABELIAN THEORIES).
- COLOURLESS HADRONS FORCE SUMMATION/ AVERAGING OVER INITIAL COLOUR STATES: CANCELLATION IS RECOVERED IN QCD (KLN THEOREM).
- EW CASE: ANALOGOUS WOULD BE FLAVOUR/ ISOSPIN SUMMATION/ AVERAGING, IMPOSSIBLE EXPERIMENTALLY.
- SL ARE NON-UNIVERSAL !
- NON-LOG (FINITE) TERMS ARE ALSO PROCESS DEPENDENT.



$\sim \sigma^{\rm Born}_{e^+e^-}$ $\neq$ $\sigma^{\rm Born}_{e^+\nu_e} \sim$



(VIRTUAL) (REAL)

- EXAMPLE: e^+e^- WOULD CANCEL AGAINST $e^+\nu_e$

- CONSIDER EXCLUSIVE FINAL STATES, Z/W RADIATION EASILY RESOLVED EXPERIMENTALLY:

  REAL & VIRTUAL LOGS ARE FINITE, NEED NOT BE RESUMMED.

- HENCE ADDITIONAL DL AND SL IN CASE OF Z EXCHANGE.

- COMPUTE ONLY VIRTUAL CONTRIBUTIONS: NEGATIVE EFFECTS DOMINATE INCLUSIVELY.

- NON-TRIVIAL HELICITY STRUCTURE: INTRODUCE PARITY-VIOLATING & SPIN ASYMMETRIES (BACKGROUND TO NEW PHYSICS).

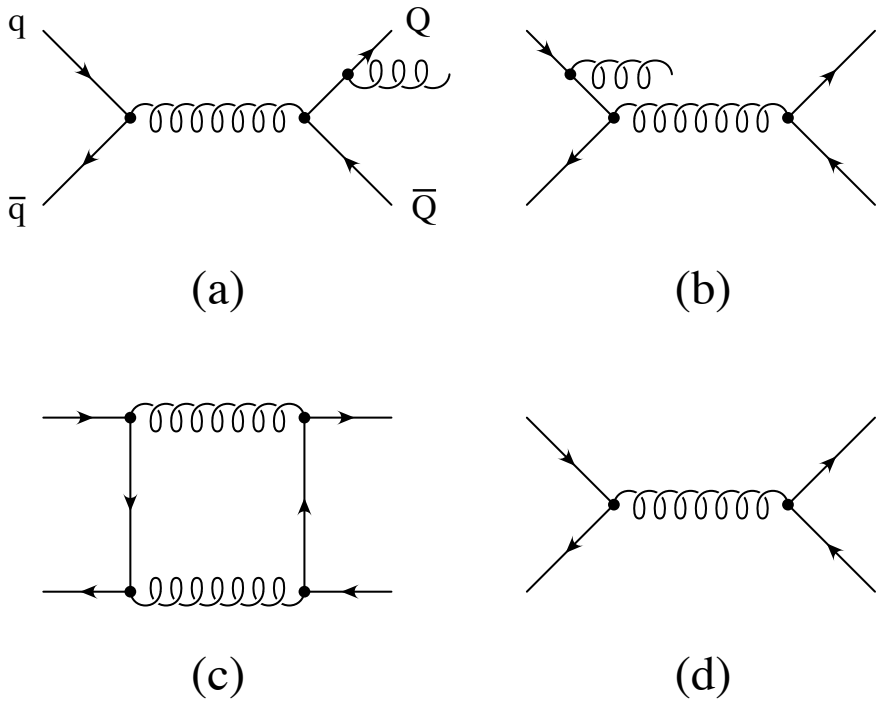
- LEADING ($\sim \alpha_{\rm W}^n \log^{2n}(s/M_W^2)$), SUB-LEADING ($\sim \alpha_{\rm W}^n \log^{2n-1}(s/M_W^2)$) AND SUB-SUB-LEADING ($\sim \alpha_{\rm W}^n \log^{2n-2}(s/M_W^2)$) LOGS CAN BE RESUMMED (INCLUSIVE FINAL STATES).

- CONSIDER HERE FIXED ORDER (INCLUDING FINITE TERMS).

- (CAN SEPARATE WEAK FROM QED CORRECTIONS IN SOME PROCESSES).

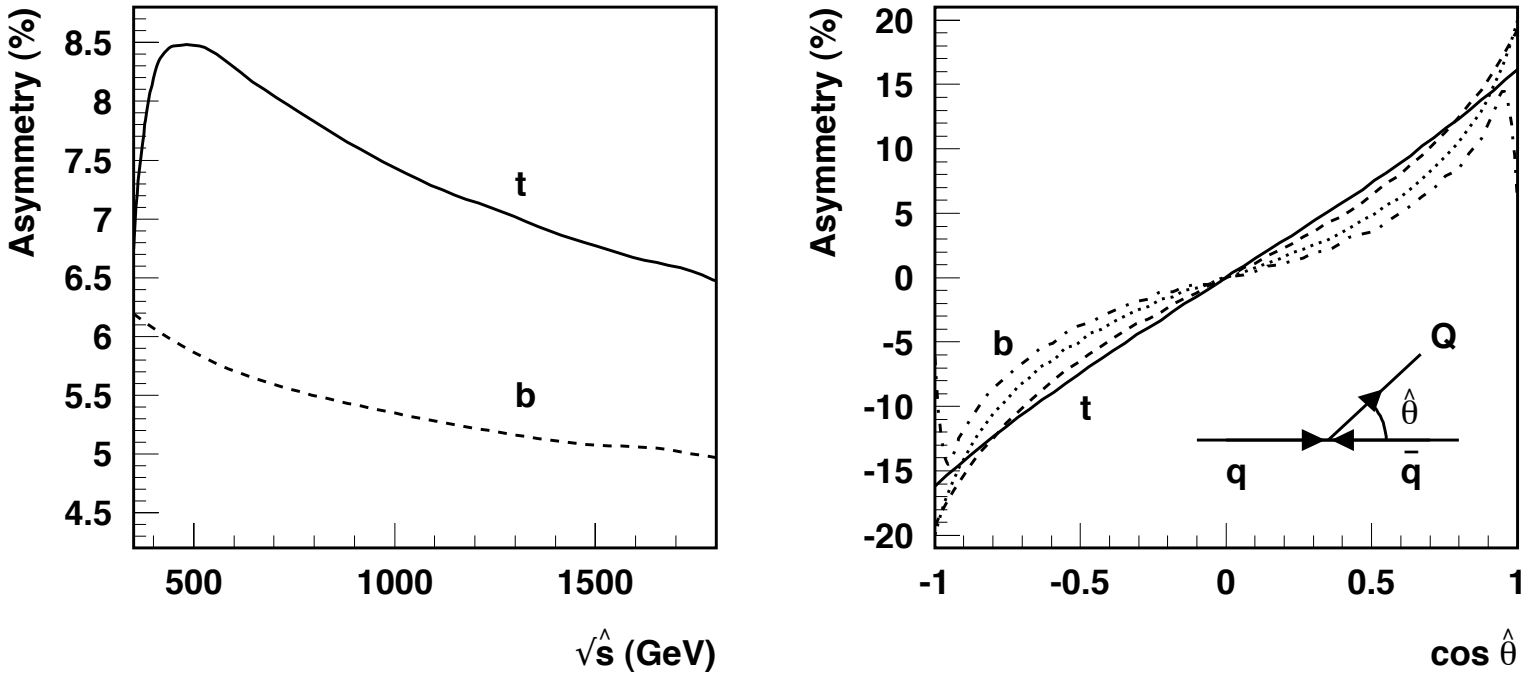
FORWARD-BACKWARD ASYMMETRY FROM QCD

[J.H. KÜHN, G. RODRIGO, PRL81:49,1998 & PRD59:054017,1999]



INTERFERENCES GIVE RISE TO FORWARD-BACKWARD ASYMMETRY (A_{FB}) PROPORTIONAL TO:

$$\left\{\tau^a \tau^b \tau^c\right\} = d^{abc}$$



FORWARD-BACKWARD ASYMMETRY IS ENHANCED AT $\cos\theta = \pm 1$.

DOUBLE-TOP PRODUCTION AT HADRON COLLIDERS

- UNDER STUDY AT TEVATRON & LHC

SALIENT FEATURES

- MEASURED BY ALL EXPERIMENTS (CDF/ DO@FNAL & ATLAS/ CMS@LHC).
- ACHIEVED CONSISTENCY WITH SM PREDICTION (REQUIRED NLO QCD AND RESUMMATION, NNLO QCD EXPECTED)

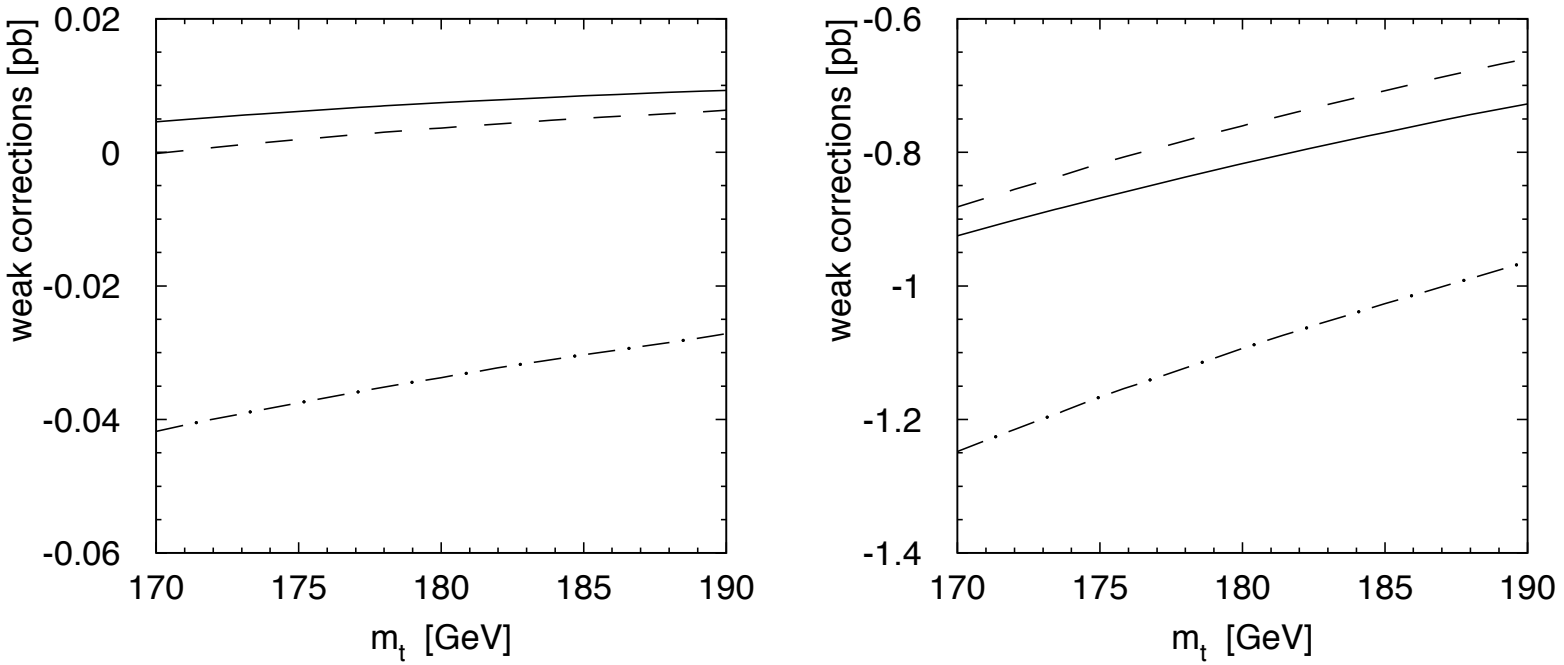
1. MANY DIFFERENT DECAY CHANNELS
2. COMPARE TO THEORY TO LOOK FOR NP – HADRONIC PRECISION EXPERIMENT
3. LARGE DATA SAMPLE – SMALL STATISTICAL ERROR
4. NEED TO CONTROL JET ENERGY SCALE – TO REDUCE SYSTEMATICAL ERROR
5. POSSIBLE TO STUDY SPIN EFFECTS (TOP DECAYS BEFORE HADRONISING !)

NLO EW EFFECTS IN $t\bar{t}$ HADRO-PRODUCTION

$$q\bar{q} \to t\bar{t}$$

[KUHN ET AL, EPJ C45:139,2006; BERNREUTHER ET AL, PLB633:54,2006]

- LO IS $5.15(0.23)[0.034]$ PB FOR $q\bar{q}$ QCD(gg QCD)[$q\bar{q}$ EW] @ TEVATRON
- LO IS $80.2(384.4)[0.49]$ PB FOR $q\bar{q}$ QCD(gg QCD)[$q\bar{q}$ EW] @ LHC

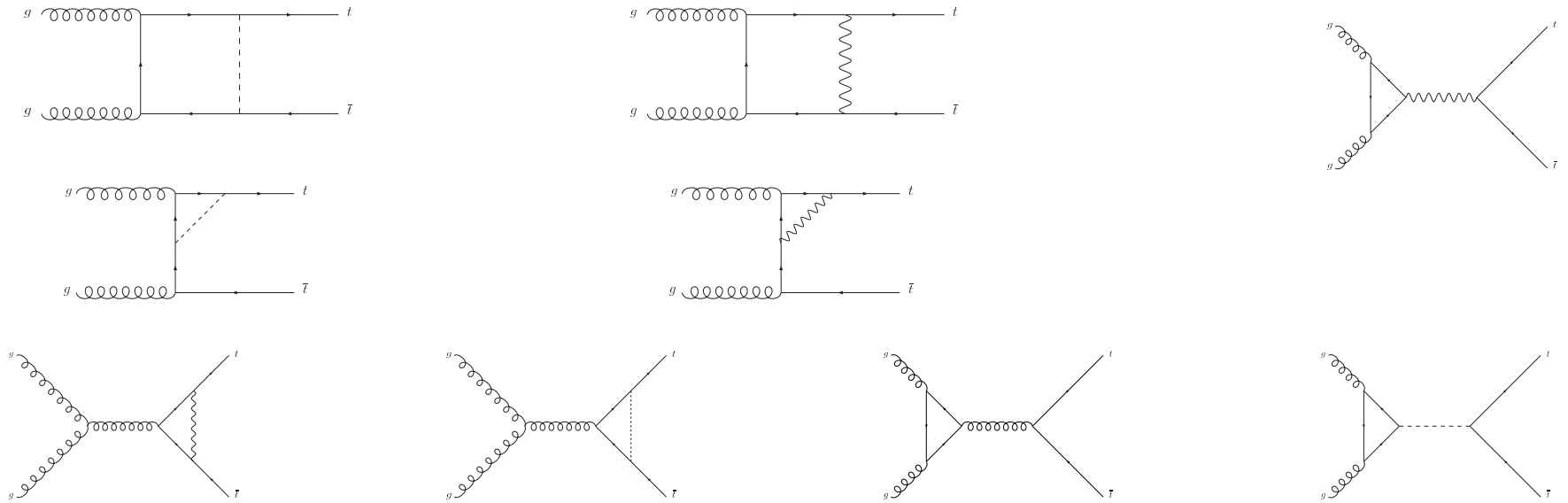


$\sigma(q\bar{q} \to t\bar{t})$(NLO-W) VS m_t FOR $M_H = 120(200)[1000]$ GEV,

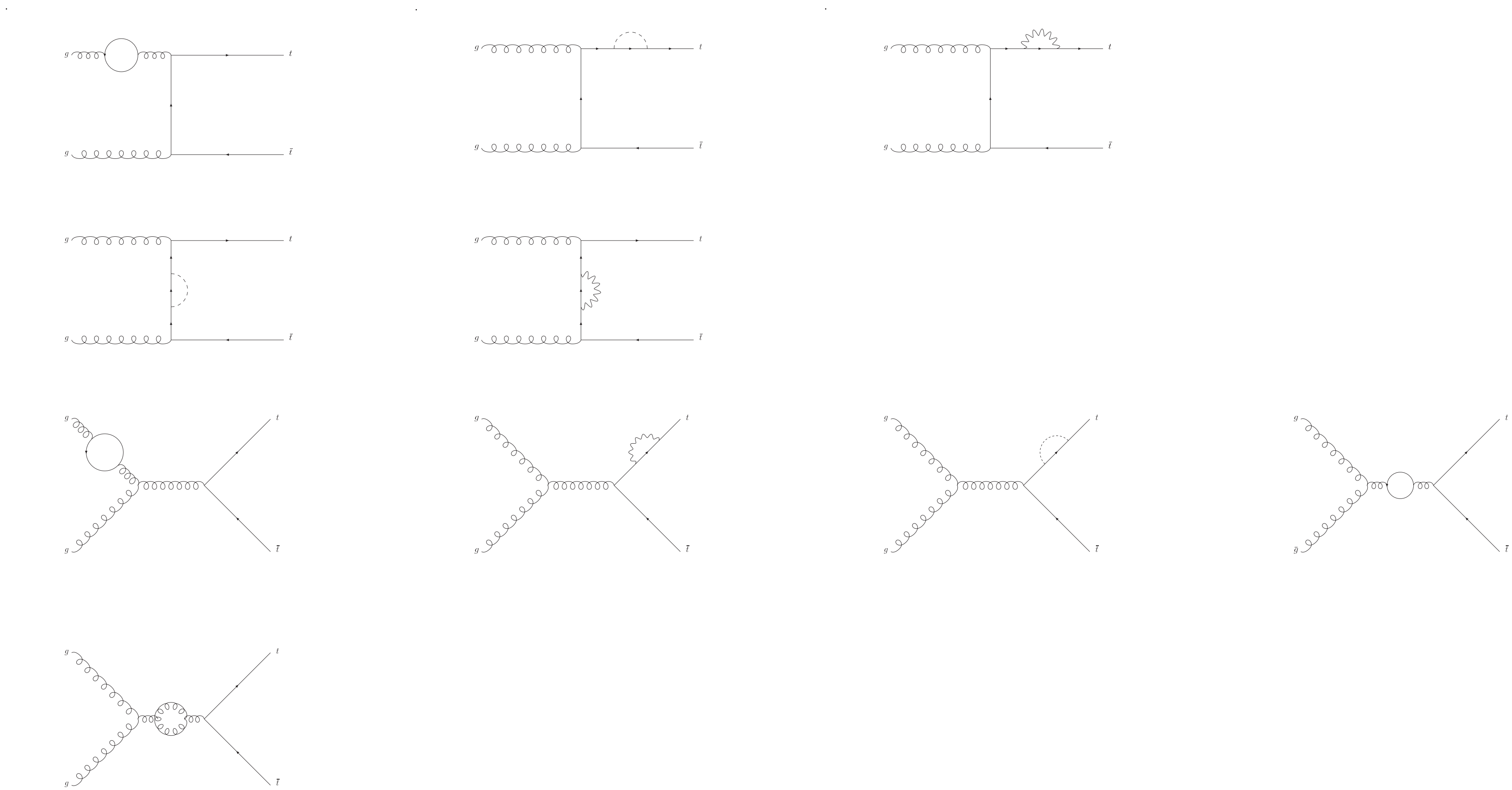
SOLID(DASHED)[DASHED-DOTTED]: LEFT@TEVATRON, RIGHT@LHC.

$gg \to t\bar{t}$

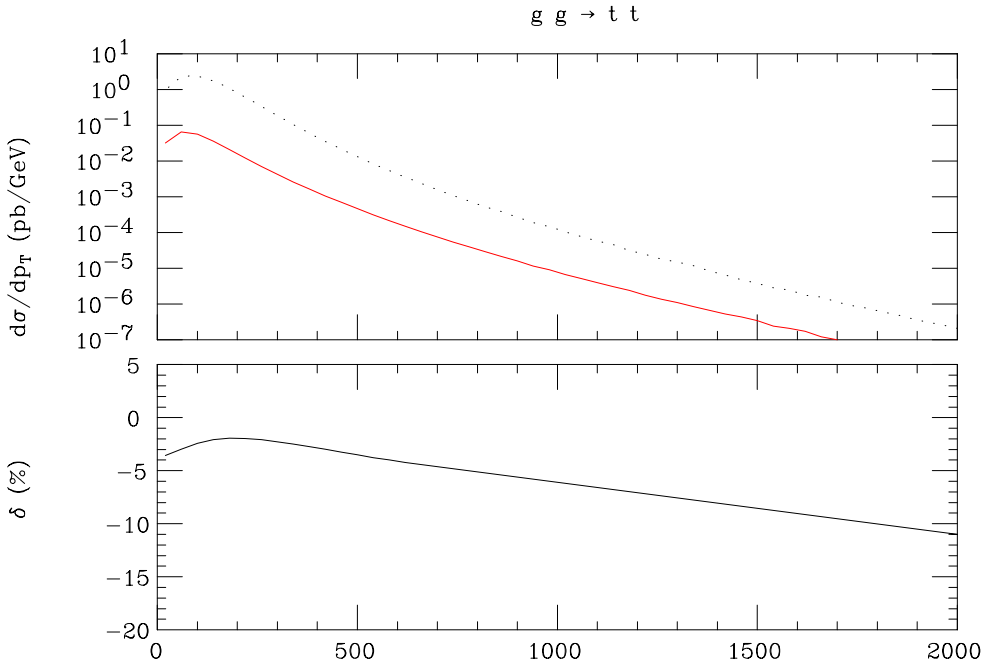
[NOLTEN, MORETTI AND ROSS, PLB639:513,2006 & PLB660:607,2008; KUHN ET AL, EPJ C51:37,2007; BERNREUTHER ET AL, PRD74:113005,2006]

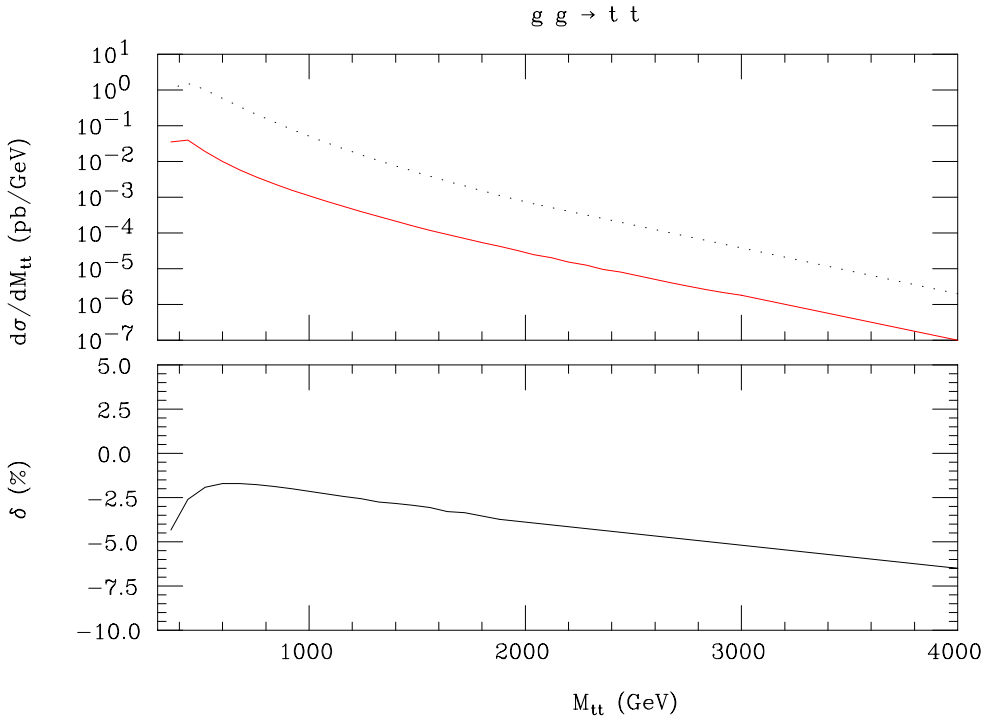


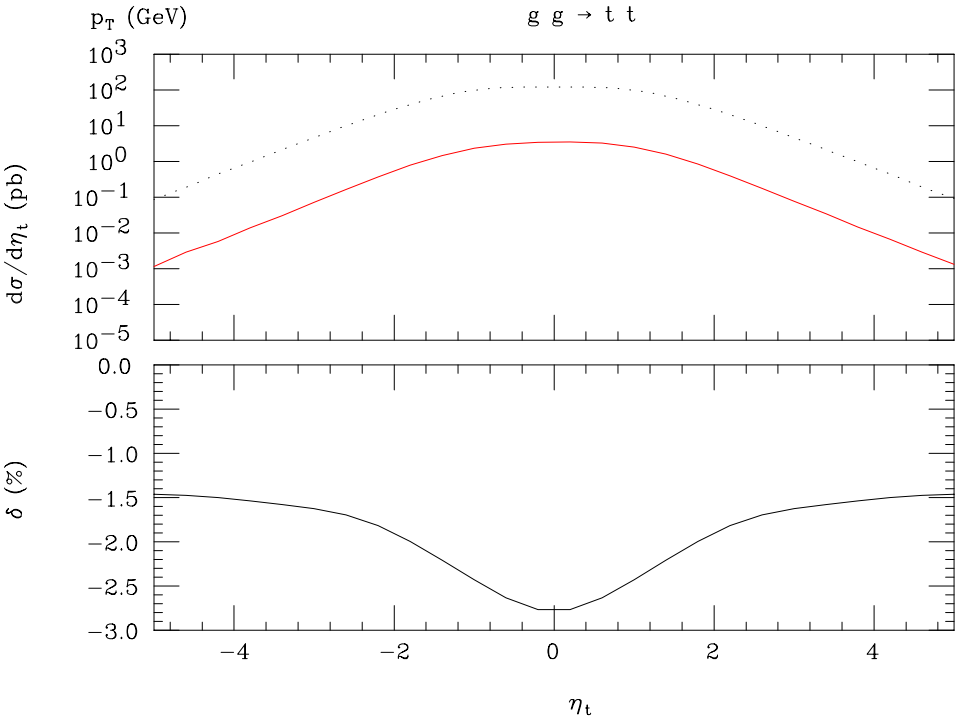
BOXES AND TRIANGLES



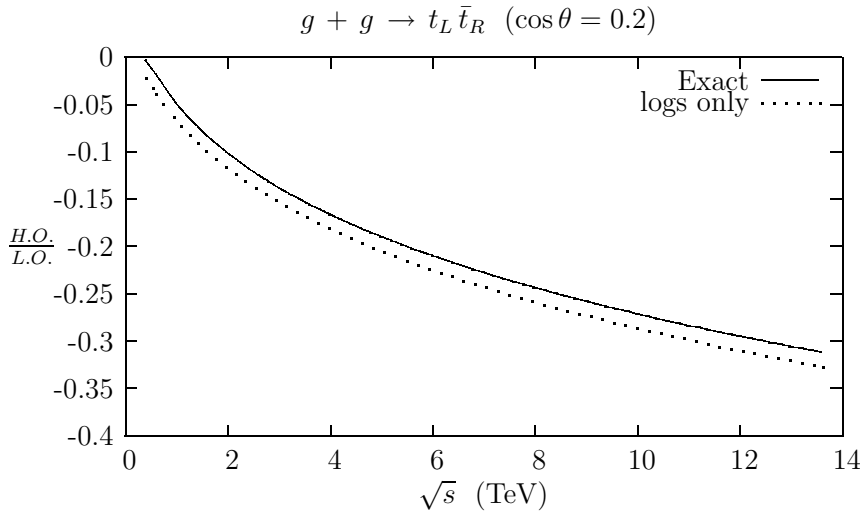
SELF-ENERGIES

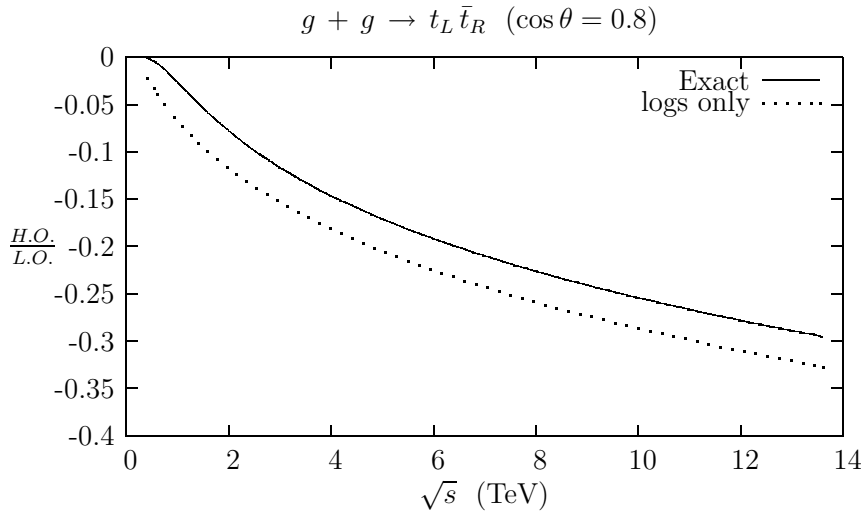

g g → t t
dσ/dp_T (pb/GeV)
δ (%)
p_T (GeV)

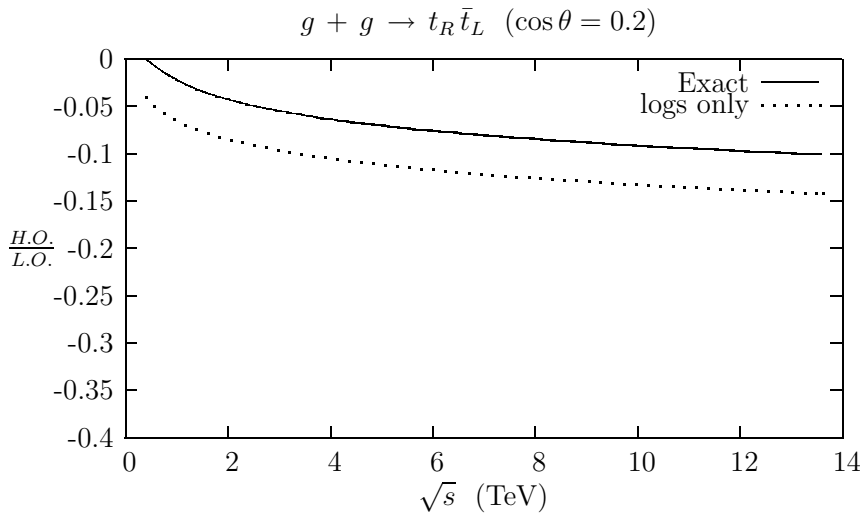

g g → t t
dσ/dM_tt (pb/GeV)
δ (%)
M_tt (GeV)

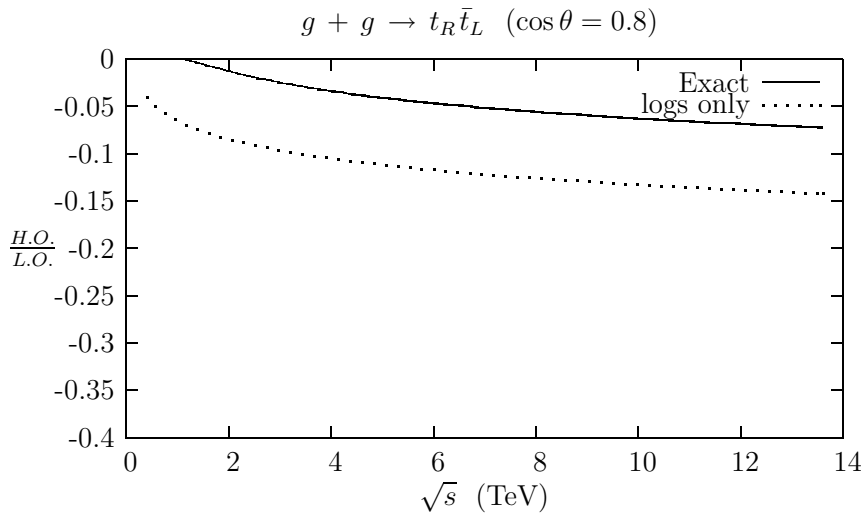

g g → t t
dσ/dη_t (pb)
δ (%)
η_t

- COMPARE FULL ONE-LOOP AGAINST DL AND (ANGULAR INDEPENDENT) SL:









POLARISED $t\bar{t}$ PRODUCTION

W. BERNREUTHER, A. BRANDENBURG, Z.G. SI, P. UWER, HEP-PH/ 0111346

CANNOT MEASURE t-POLARISATIONS DIRECTLY, BUT CAN DETERMINE IF SPINS ARE ALIGNED OR ANTI-ALIGNED FROM ANGULAR DISTRIBUTIONS OF DECAY PRODUCTS.

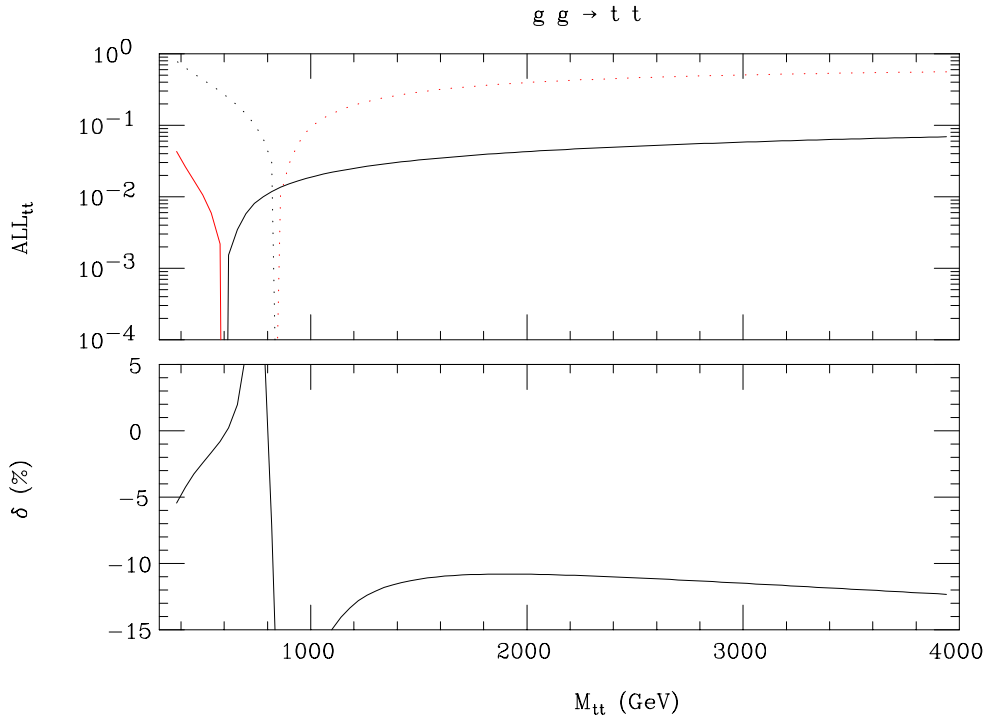
$$t\bar{t} \to b W^+ \bar{b} W^- \to b e^+ \nu \bar{b} e^- \bar{\nu}$$

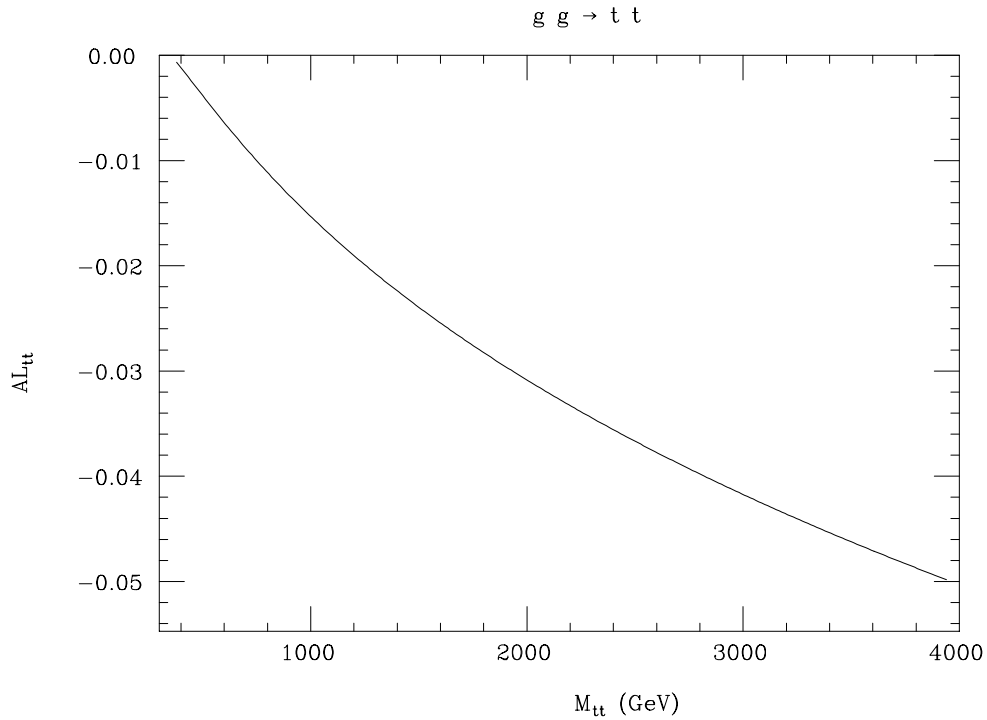
- CAN DEFINE SINGLE AND DOUBLE TOP-SPIN ASYMMETRIES:

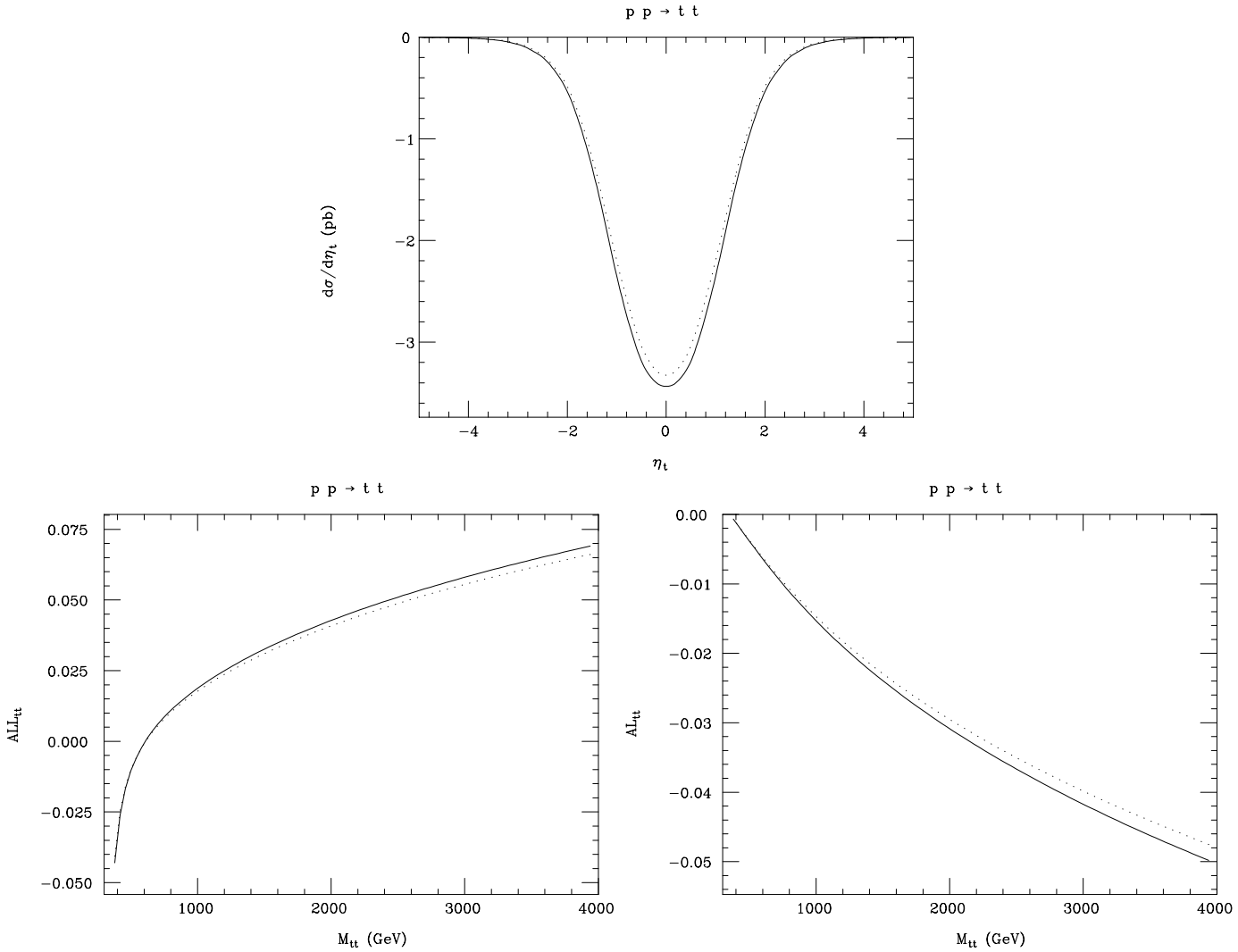
$$\begin{aligned} A_{LL}\, d\sigma &\equiv d\sigma_{++} - d\sigma_{+-} + d\sigma_{--} - d\sigma_{-+}, \\ A_{L}\, d\sigma &\equiv d\sigma_{-} - d\sigma_{+}, \\ A_{PV}\, d\sigma &\equiv d\sigma_{--} - d\sigma_{++}. \end{aligned}$$

- FIRST IS PARITY-CONSERVING, LAST TWO ARE PARITY-VIOLATING
- INDICES $+$ AND $-$ REFER TO HELICITIES OF RIGHT (R) AND LEFT (L) t'S

NLO QCD CONTRIBUTIONS TO A_{LL}, A_L, A_{PV} HAVE BEEN CALCULATED.
WEAK CONTRIBUTIONS EXPECTED TO BE OF SIMILAR MAGNITUDE


g g → t t
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
ALL_{tt}
5
0
−5
−10
−15
δ (%)
1000
2000
3000
4000
M_{tt} (GeV)


g g → t t
0.00
−0.01
−0.02
−0.03
−0.04
−0.05
AL_{tt}
1000
2000
3000
4000
M_{tt} (GeV)



(SOME DEPENDENCE ON THE H MASS: SOLID(DOTTED) FOR $M_H = 150(200)$ GEV.)

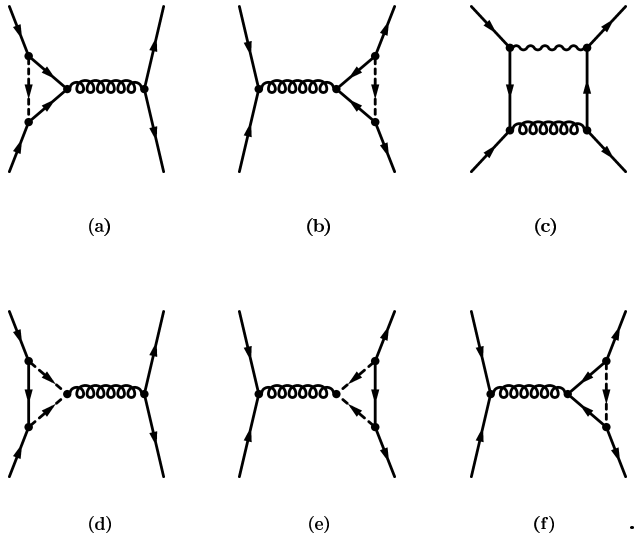
MSSM CORRECTIONS TO HEAVY QUARK PAIR PRODUCTION

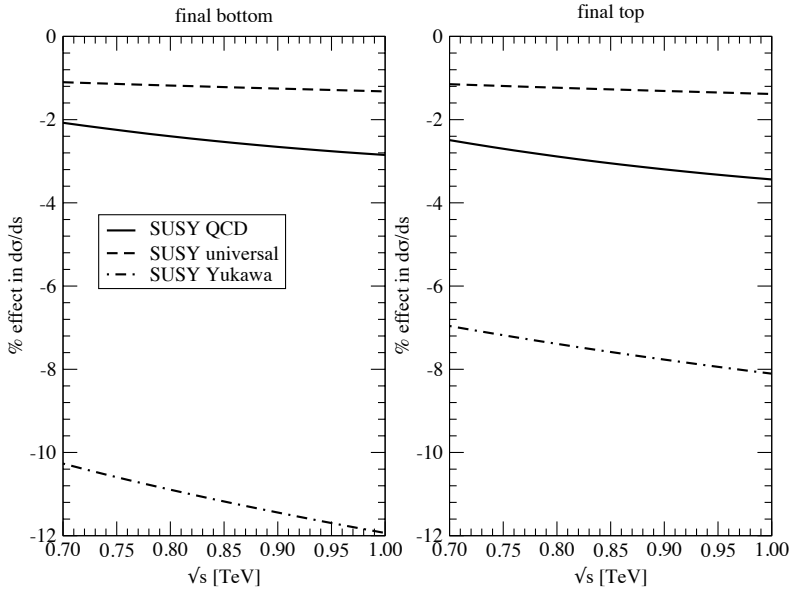
[BECCARIA ET AL, PRD69:113004,2004 & HEP-PH/0405036 & PHYS.REV.D71:073003,2005]

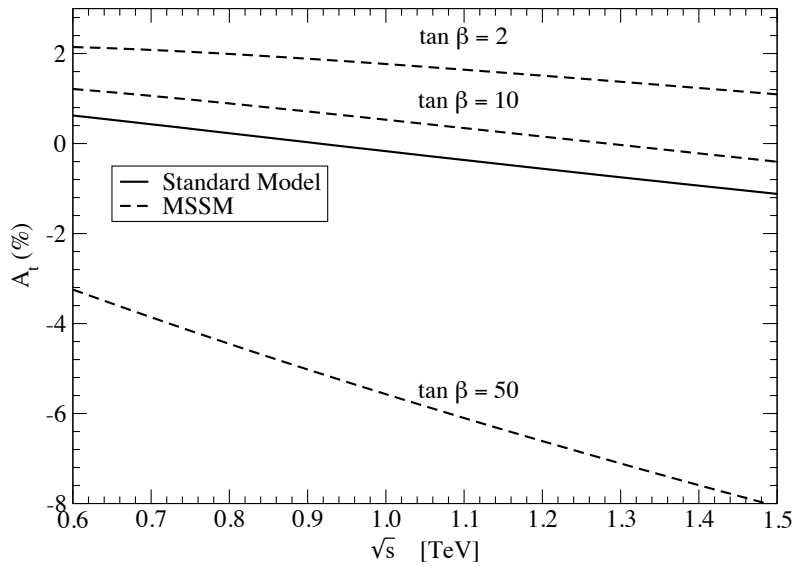
ONE-LOOP CORRECTIONS (QCD & EW) WITH (VIRTUAL) SUSY PARTICLES AFFECT PRODUCTION CROSS-SECTIONS.

THE MAGNITUDE OF THESE EFFECTS DEPEND ON SUSY PARAMETERS:

PRECISION PHYSICS PROGRAMME AT LHC TO FIT UNDERLYING SUSY MODEL ?







CALCULATED IN THE LEADING (SUDAKOV) LOG APPROXIMATION:

$$\ln\left(\frac{x_1 x_2 s}{M^2_{SUSY}}\right) >> 1$$

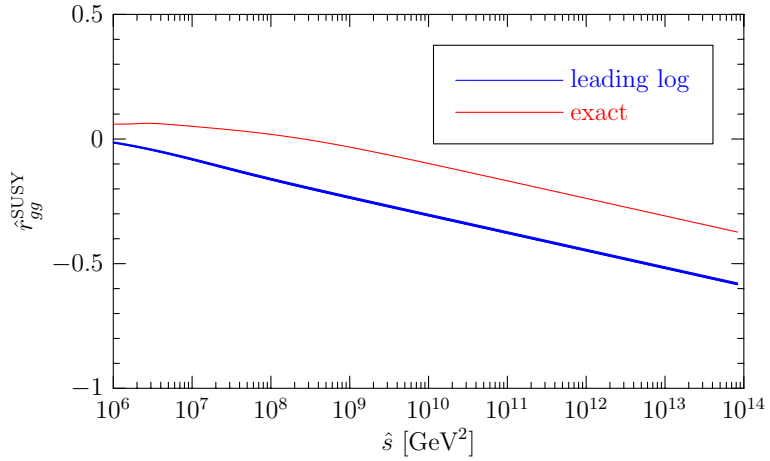
(ALSO, USED HERE LIGHT MSSM SPECTRUM.)

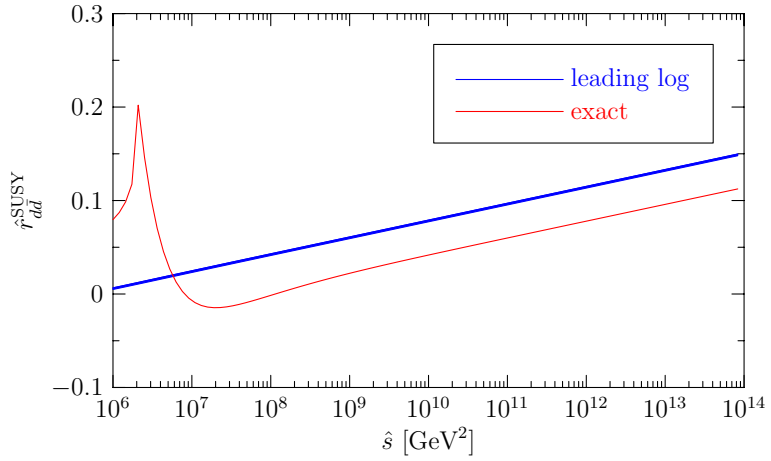
SUM RULES EXIST BETWEEN SINGLE- AND DOUBLE-TOP ASYMMETRIES [BECCARIA ET AL, PRD72:093001,2005]

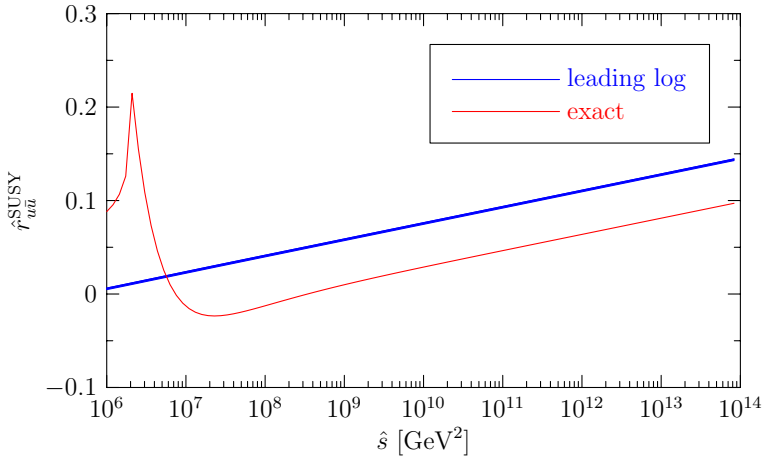
MSSM CORRECTIONS TO HEAVY QUARK PAIR PRODUCTION

[ROSS AND WIEBUSCH, JHEP0711:041,2007]

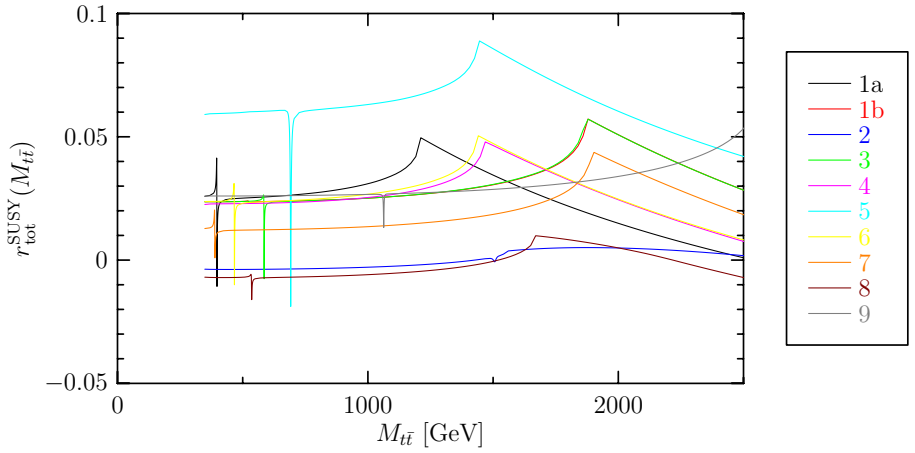
CONSIDER NOW QCD AND EW NLO IN MSSM:

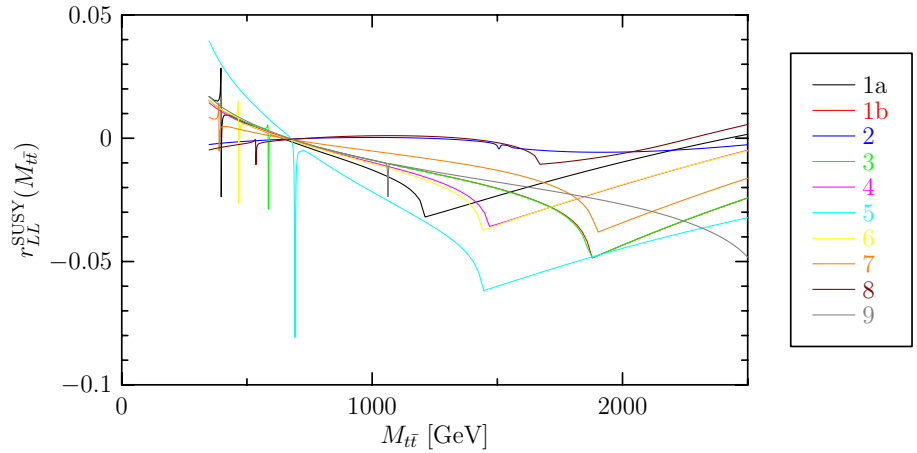


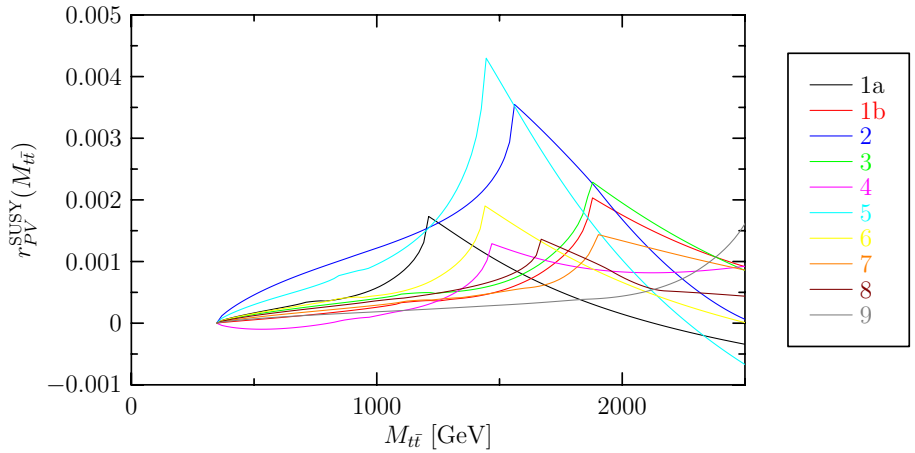




CLOCKWISE: gg, $u\bar{u}$, $d\bar{d}$ AT THE LHC FOR SPS5.







HADRO-PRODUCTION AT THE LHC FOR ALL SPSS.

SINGLE-TOP PRODUCTION AT HADRON COLLIDERS

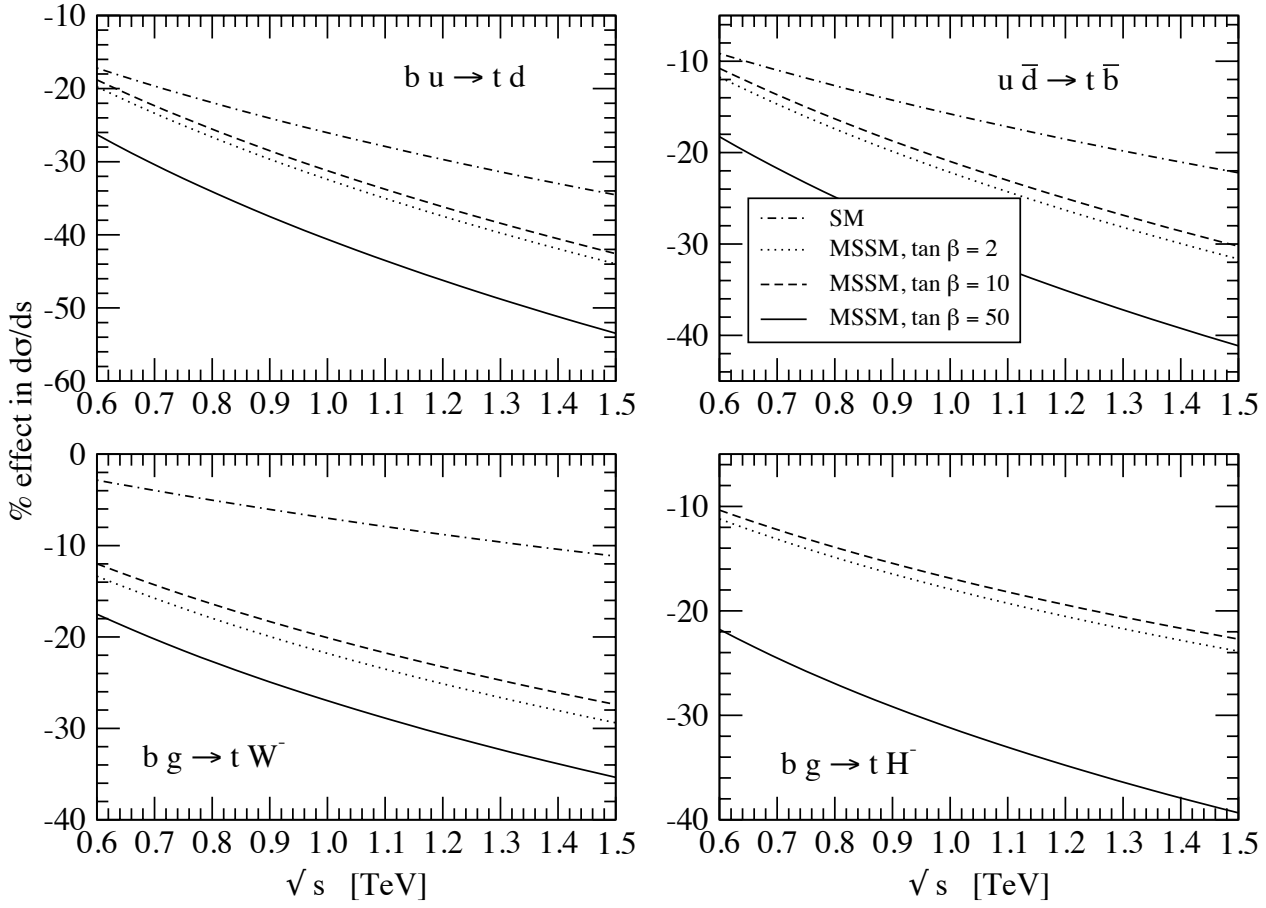
- UNDER STUDY AT TEVATRON & LHC

SALIENT FEATURES

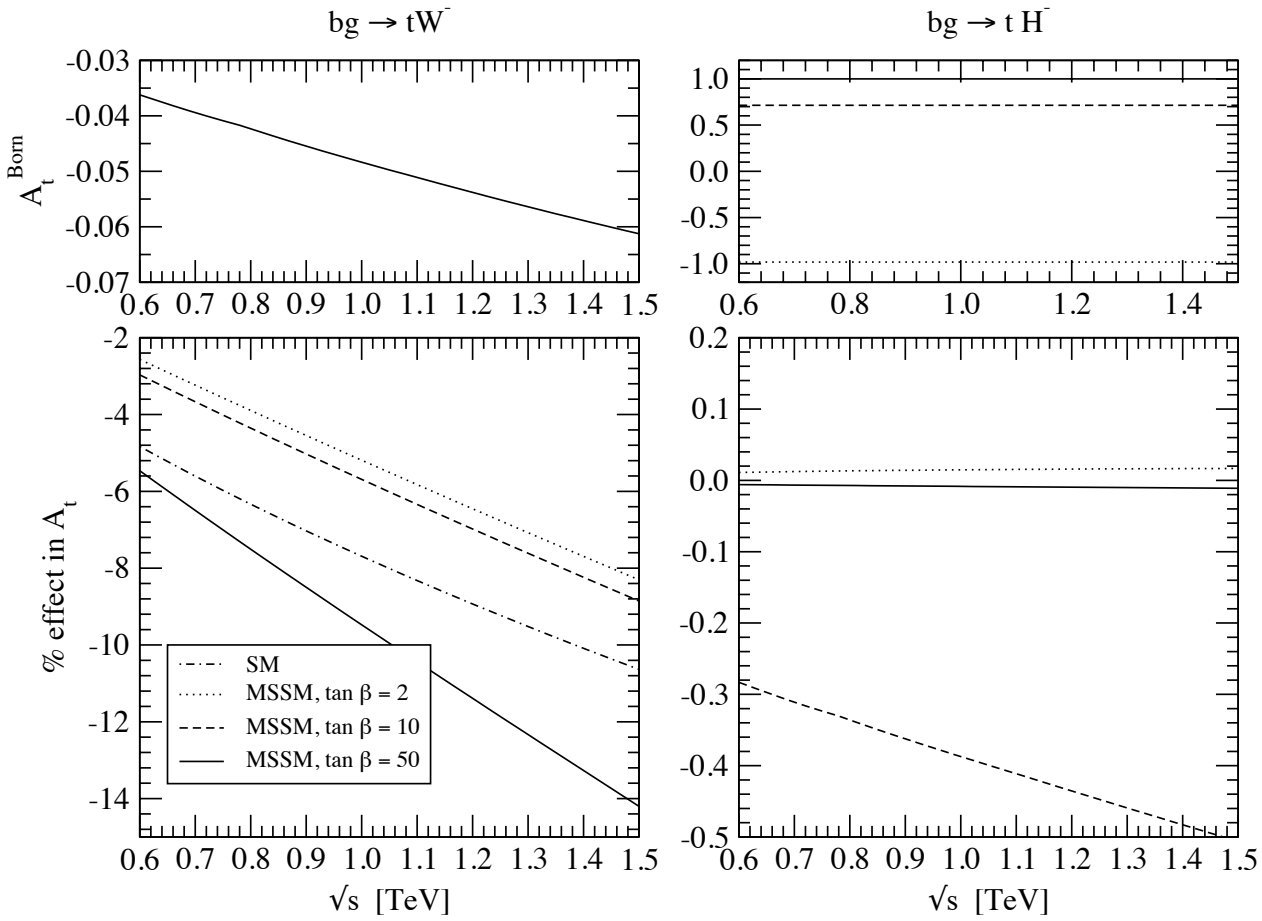
- (BEING) MEASURED BY ALL EXPERIMENTS (CDF/ DO@FNAL & ATLAS/ CMS@LHC).
- ACHIEVED CONSISTENCY WITH SM PREDICTION

1. REQUIRES DETAILED KNOWLEDGE OF b DYNAMICS INSIDE (ANTI)PROTON
2. ENABLES MEASURING TOP CKMS FROM CROSS-SECTION
3. COMPARE TO THEORY TO LOOK FOR NP
4. LARGE DATA SAMPLE (1/ 3 OF DOUBLE TOP)
5. AGAIN, NEED TO CONTROL JET ENERGY SCALE
6. AGAIN, POSSIBLE TO STUDY SPIN EFFECTS (SINGLE ASYMMETRIES)

(LO DIAGRAMS FOR SINGLE-TOP PRODUCTION: bq (A) [245 PB], $q\bar{q}'$ (B) [10 PB] & bg (C) [50 PB] FUSION.)



SM & MSSM EW ONLY SUDAKOVS. [BECCARIA ET AL, PRD71:033005,2005]

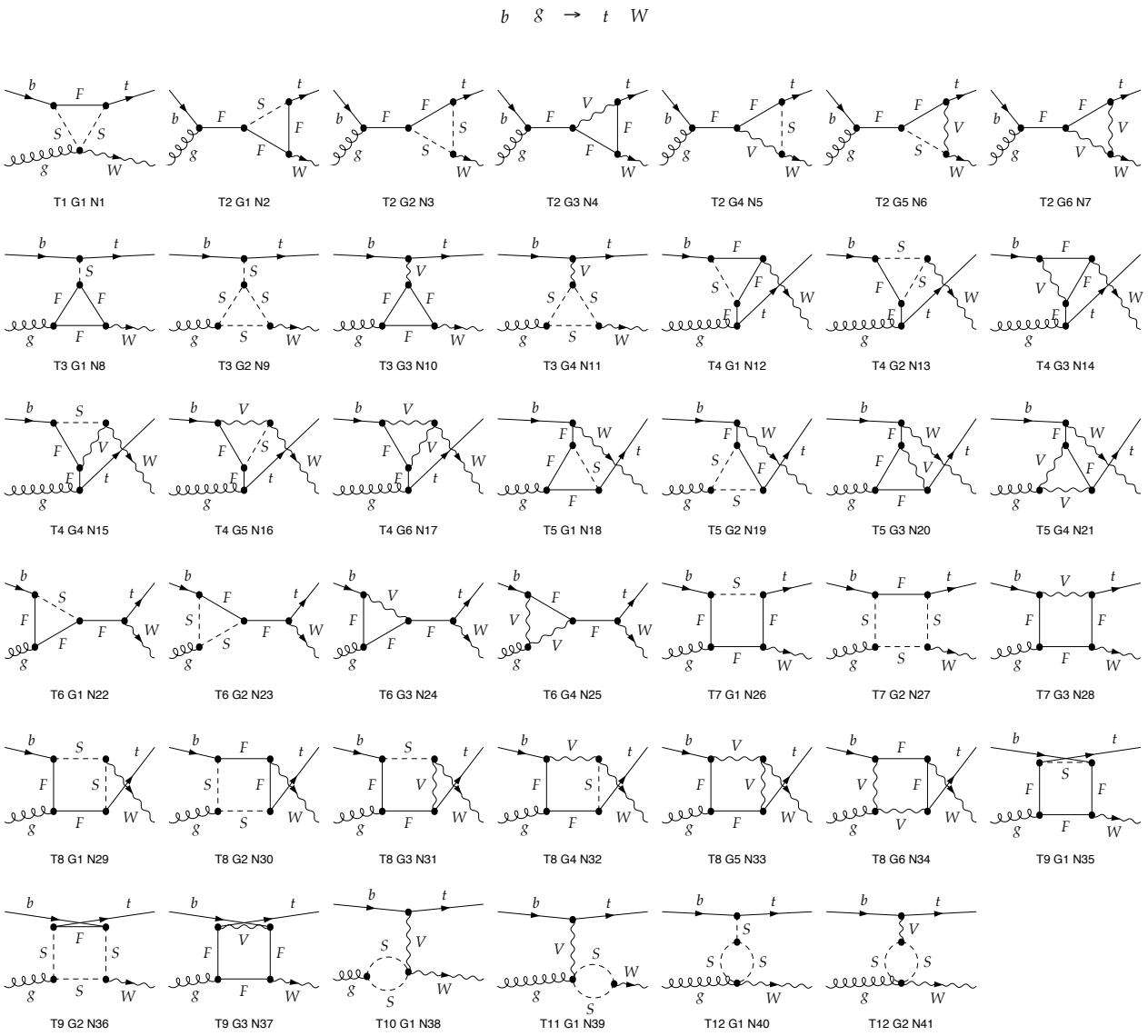


ASYMMETRY $A_L(t)$ FOR bg-FUSION. [BECCARIA ET AL, PRD71:033005,2005]

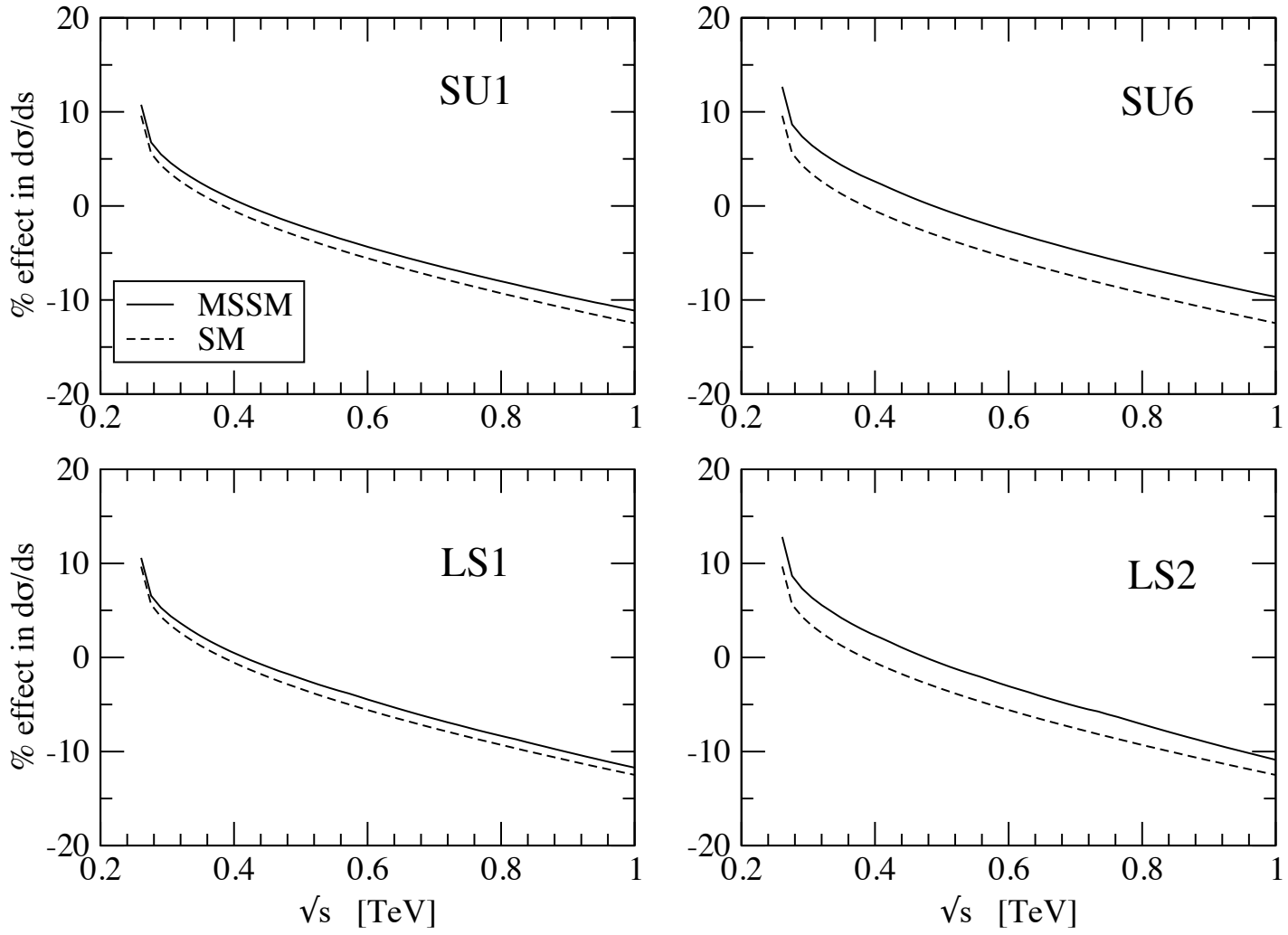
	SU1	SU6	LS1	LS2
m_0	70	320	300	300
$m_{1/2}$	350	375	150	150
A_0	0	0	-500	-500
$\tan\beta$	10	50	10	50
$\mu/\lvert\mu\rvert$	1	1	1	1
α	-0.110	-0.0212	-0.109	-0.015
M_1	144.2	155.8	60.1	60.6
M_2	270.1	291.3	114.8	115.9
μ	474.4	496.6	329.7	309.3
$H^{\pm}$	534.3	401.7	450.4	228.9
H^0	528.3	392.5	442.5	211.1
h^0	114.6	115.7	111.4	110.8
A^0	527.9	392.5	443.4	212.0
$\chi_1^{\pm}$	262.8	289.3	108.0	111.1
$\chi_2^{\pm}$	495.3	514.8	350.1	329.4
χ_1^0	140.1	153.0	57.38	58.92
χ_2^0	263.1	289.4	108.5	111.3
χ_3^0	479.2	501.0	335.3	315.8
χ_4^0	495.4	514.0	348.7	326.5

	SU1	SU6	LS1	LS2
$\widetilde{l}_L$	253.3	412.3	321.0	321.2
$\widetilde{l}_R$	157.6	353.4	308.7	308.7
$\widetilde{\nu}_e$	241.0	404.8	311.3	311.3
$\widetilde{\tau}_L$	149.6	195.8	297.1	078.1
$\widetilde{\tau}_R$	256.1	399.2	323.8	282.5
$\widetilde{\nu}_\tau$	240.3	362.5	308.4	243.6
$\widetilde{u}_L$	762.9	870.5	459.8	460.2
$\widetilde{u}_R$	732.9	840.7	451.9	452.3
$\widetilde{d}_L$	766.9	874.0	466.4	467.0
$\widetilde{d}_R$	730.2	837.8	452.8	453.2
$\widetilde{t}_L$	562.5	631.5	213.3	223.6
$\widetilde{t}_R$	755.8	796.9	462.9	431.3
$\widetilde{b}_L$	701.0	713.7	380.6	304.0
$\widetilde{b}_R$	730.2	787.6	449.1	401.7
θ_τ	1.366	1.133	1.091	1.117
θ_b	0.3619	0.7837	0.184	0.653
θ_t	1.070	1.050	1.016	0.9313

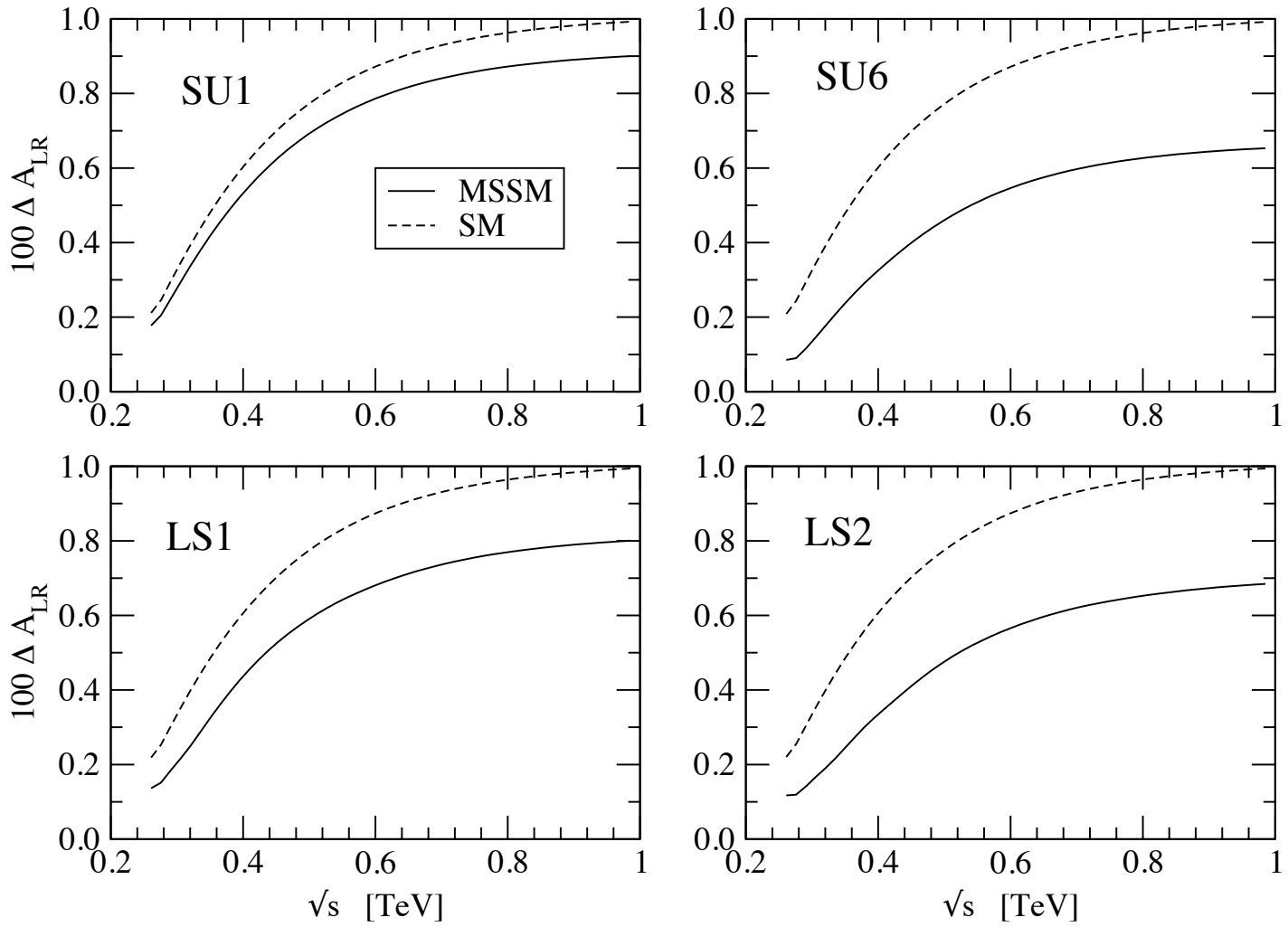
DEFINE MSUGRA BENCHMARKS.



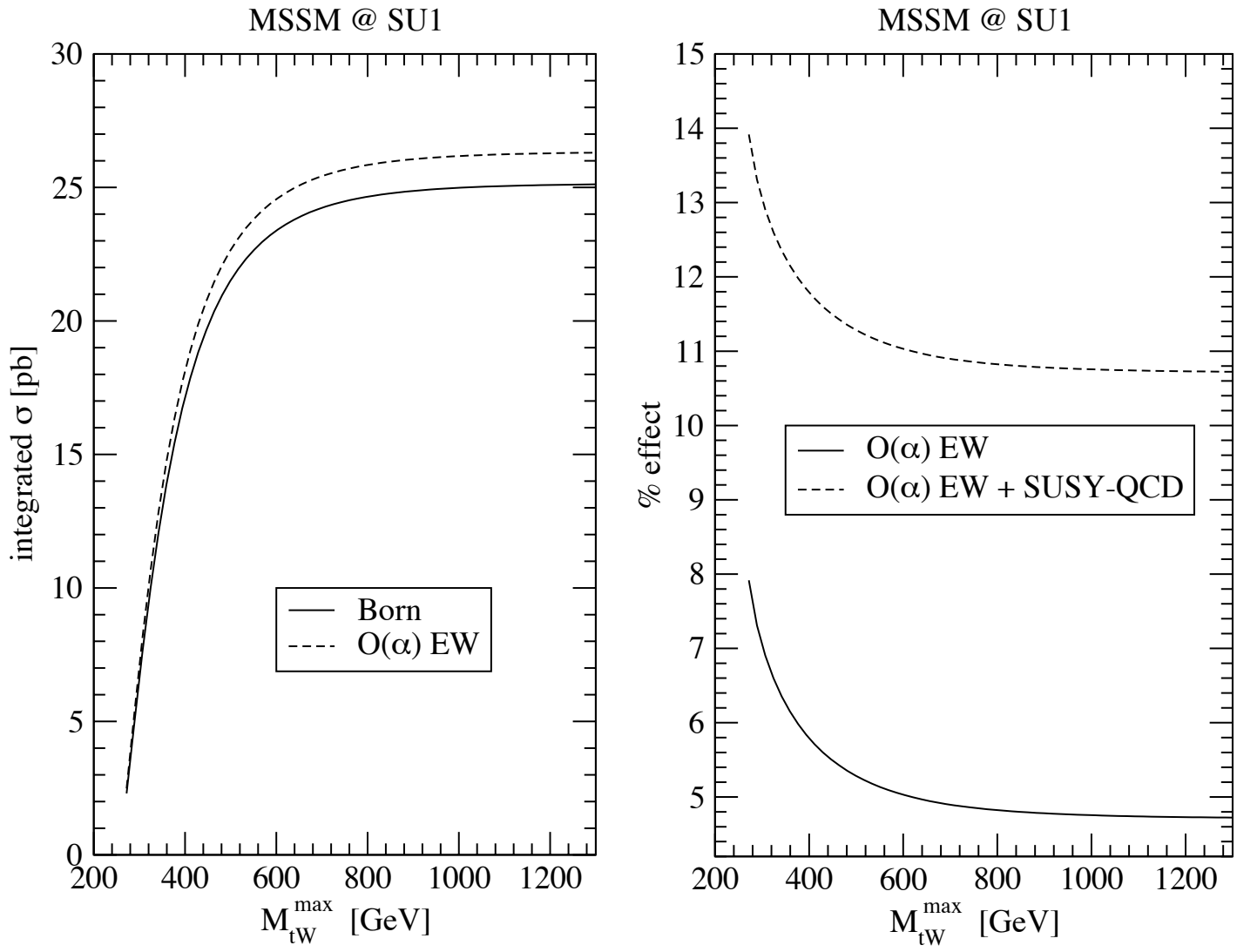
ONE LOOP SM & MSSM EW DIAGRAMS IN $bg \to tW^-$. [BECCARIA ET AL, PRD73:093001,2006]



ONE LOOP SM & MSSM EW EFFECTS IN $bg \to tW^-$: CROSS SECTION.

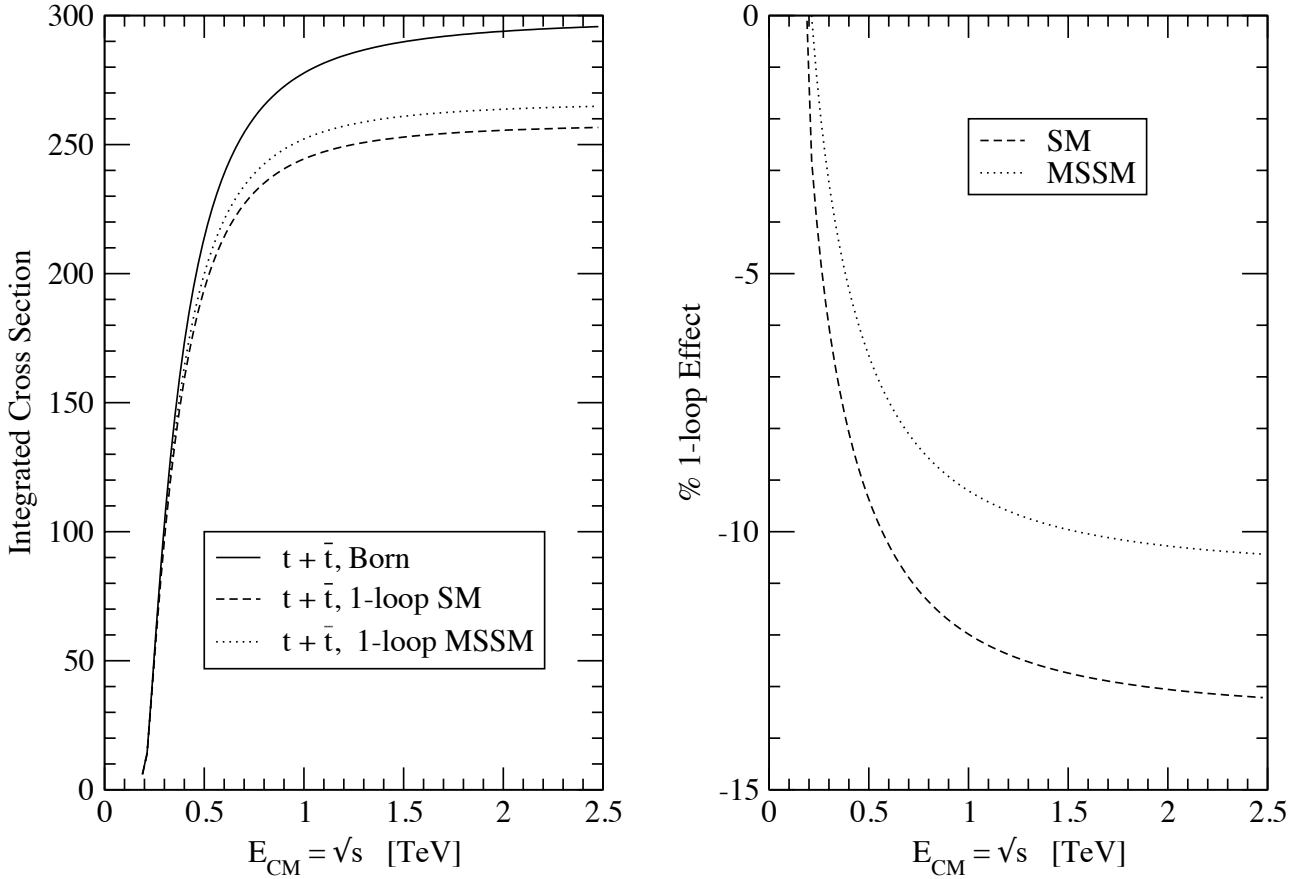


ONE LOOP SM & MSSM EW EFFECTS IN $bg \to tW^-$: A_L ASYMMETRY.

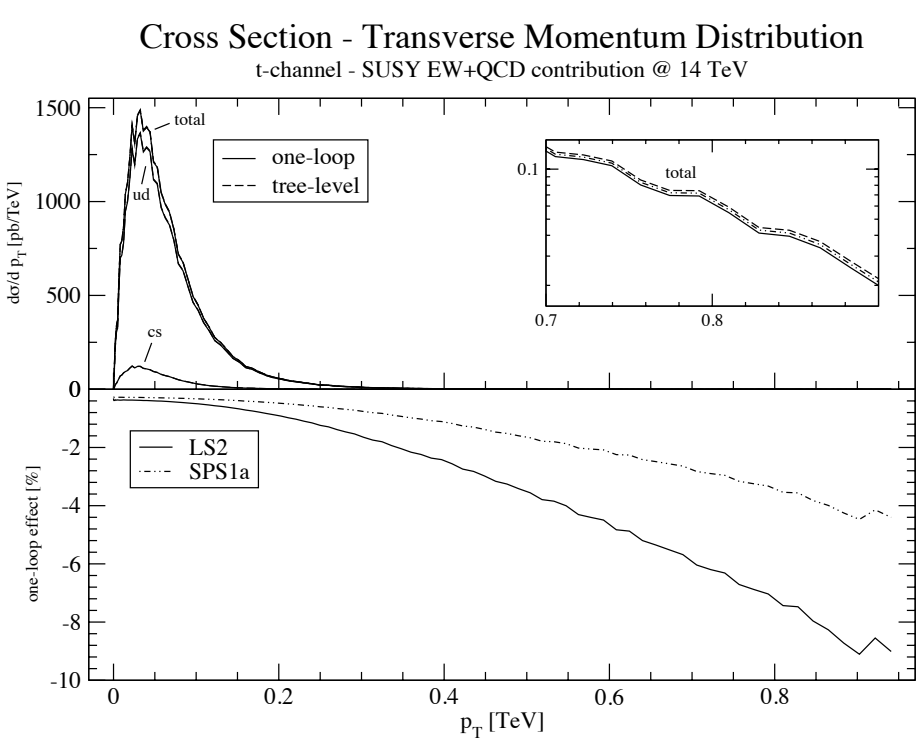


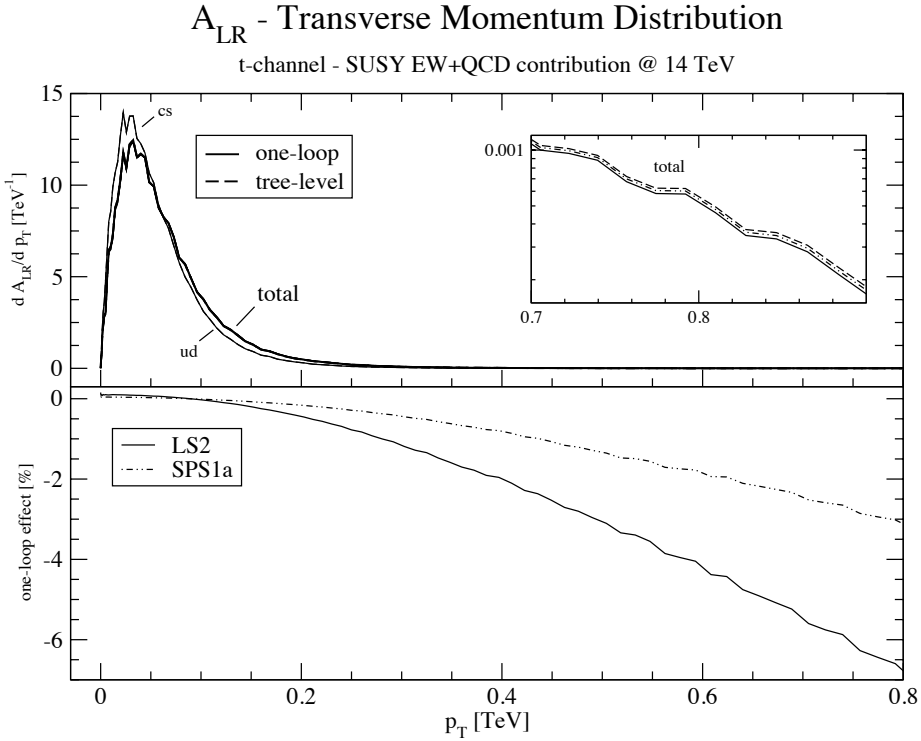
INCLUDE ONE LOOP MSSM QCD EFFECTS: CROSS SECTION. [EPJC53:257,2008]

$t + \bar{t}$ production

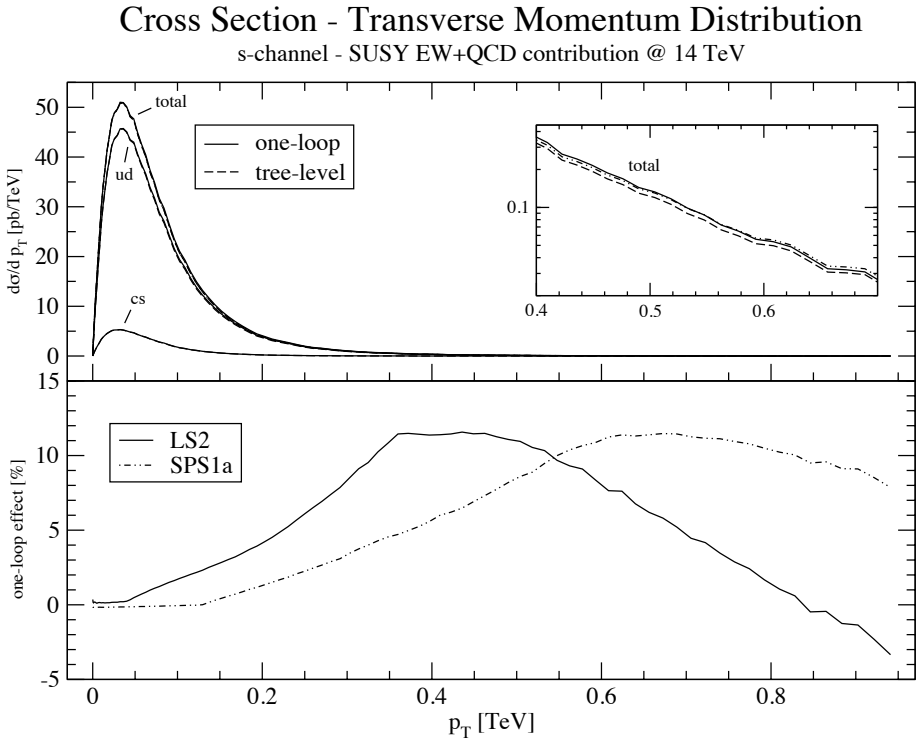


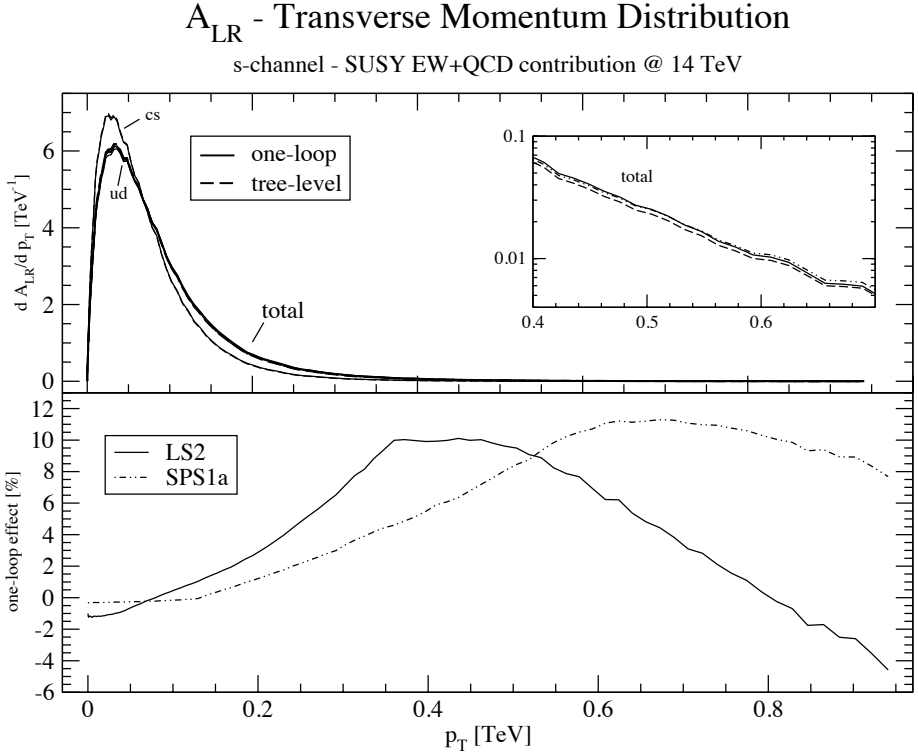
ONE LOOP SM & MSSM EW EFFECTS IN $bq \to tq'$: CROSS SECTION. [BECCARIA ET AL, PRD74:013008,2006 & HEP-PH/ 0609189]



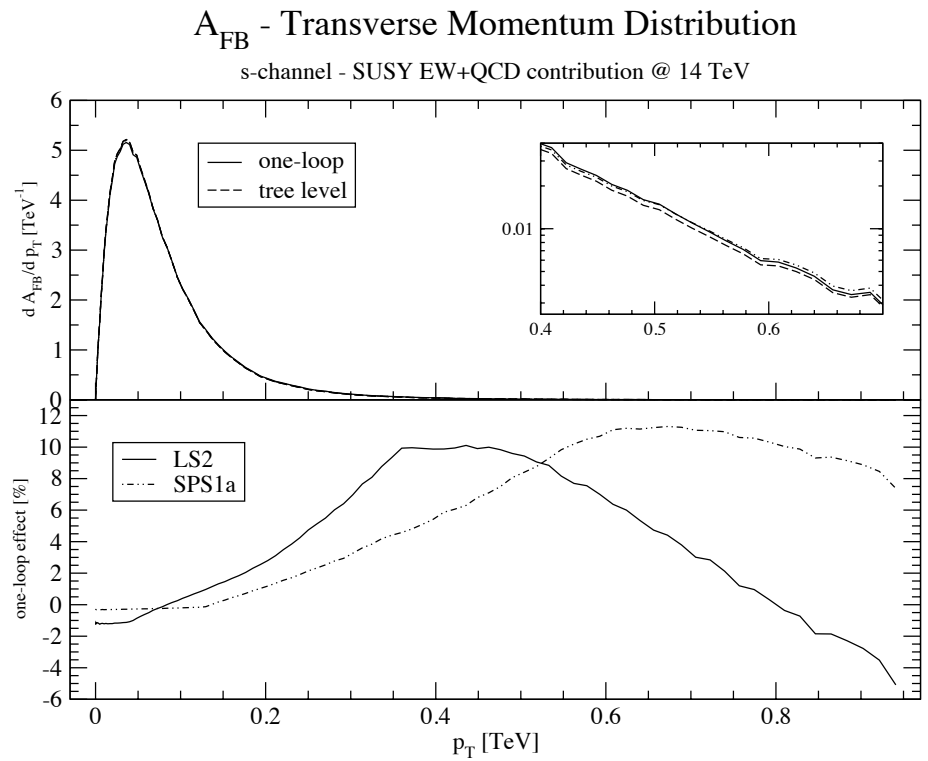


ONE LOOP MSSM QCD & EW EFFECTS IN $bq \to tq'$: CROSS SECTION & A_L ASYMMETRY. [MACORINI, MORETTI AND PANIZZI, PRD82:054016,2010]

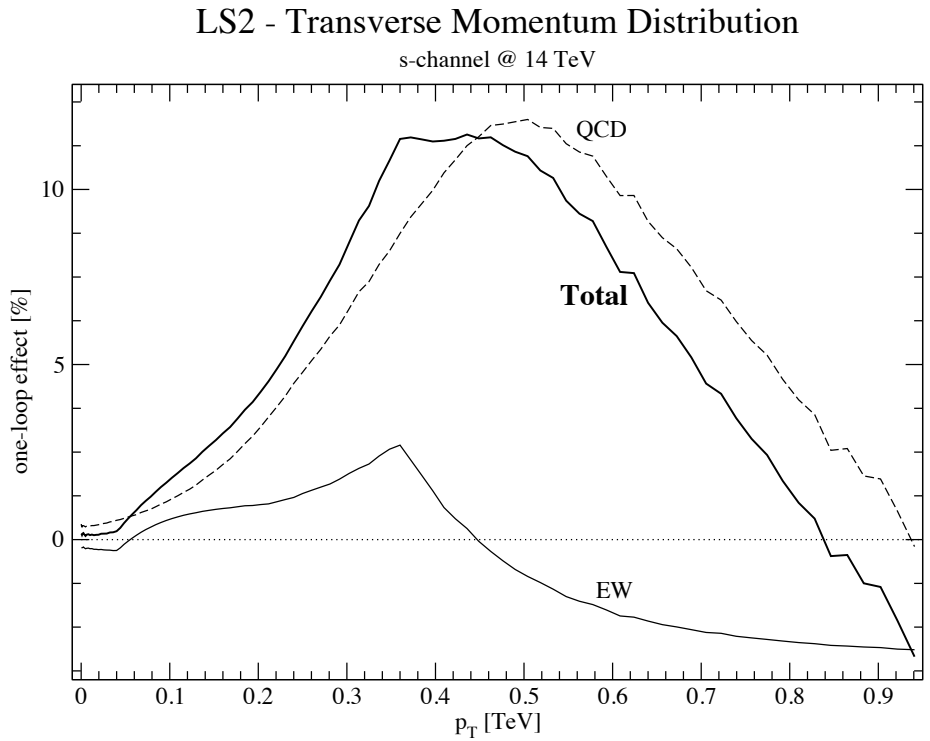


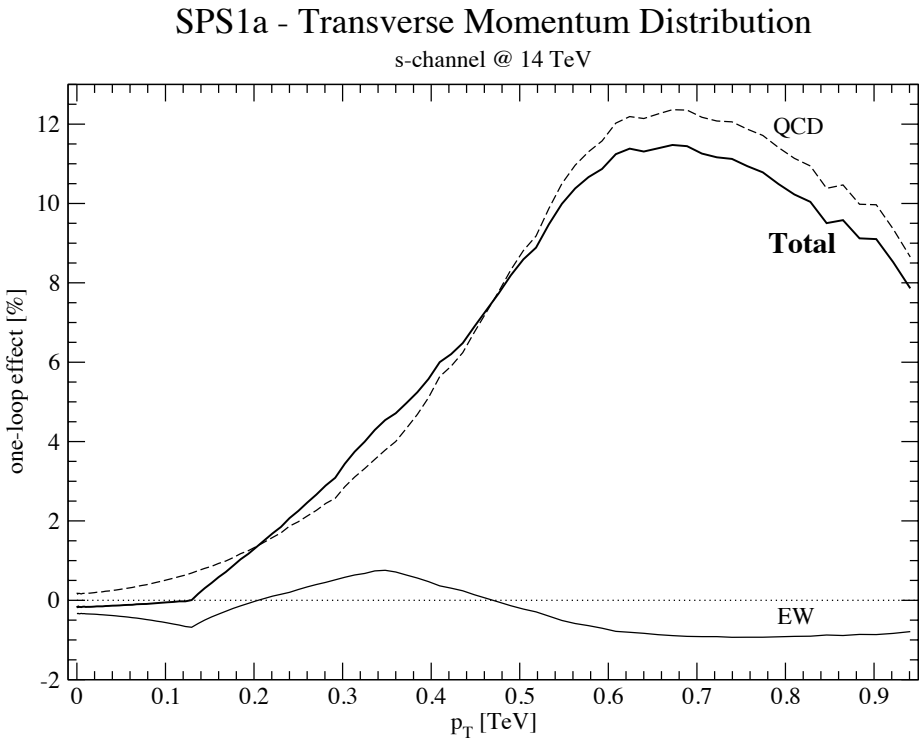


ONE LOOP MSSM QCD & EW EFFECTS IN $q\bar{q}' \to t\bar{b}$: CROSS SECTION & A_L ASYMMETRY. [MACORINI, MORETTI AND PANIZZI, PRD82:054016,2010]



ONE LOOP MSSM QCD & EW EFFECTS IN $q\bar{q}' \to t\bar{b}$: A_{FB} ASYMMETRY. [MACORINI, MORETTI AND PANIZZI, PRD82:054016,2010]





ONE LOOP MSSM QCD & EW (SEPARATE) EFFECTS IN $q\bar{q}' \to t\bar{b}$: CROSS SECTION.
[MACORINI, MORETTI AND PANIZZI, PRD82:054016,2010]

CONCLUSIONS

- BOTH SM & MSSM, BOTH QCD & EW CORRECTIONS TO BOTH DOUBLE- AND SINGLE-TOP PROCESSES AVAILABLE.
- INCLUDE ALL DIFFERENTIAL DISTRIBUTIONS AND ASYMMETRIES (BOTH SPIN AND FORWARD/ BACKWARD).
- THEY ARE RELEVANT FOR HIGH ENERGY AND HIGH p_T CONFIGURATIONS (EXCEPT SM QCD).

OUTSTANDING ISSUES:

- NEED TO CLARIFY TREATMENT OF W, Z REAL RADIATION: EXP. INPUT.
- EW TOOLS NEEDED: IMPLEMENT RESULTS IN EXCLUSIVE MONTE CARLO. (MC) EVENT GENERATION, EASIER: NO DOUBLE COUNTING FOR W, Z RADIATION WITH PARTON. SHOWER, PROBLEM SOLVED FOR QED RADIATION (ABELIAN QCD).

- DEFINE EW PDFS AND (MORE IMPORTANTLY) PS.
- NEEDED FOR PRECISION MEASUREMENT PROGRAMME: E.G., SEARCH FOR VIRTUAL SUSY EFFECTS.

CURRENT WORK:

- CHECKING OUT TEVATRON ANOMALY IN $A_{FB}(t\bar{t})$ THROUGH $\mathcal{O}(\alpha_s^3)$, $\mathcal{O}(\alpha_s^2\alpha_W)$, $\mathcal{O}(\alpha_s\alpha_W^2)$ & $\mathcal{O}(\alpha_W^2)$ IN BOTH SM & MSSM (PLUS OTHER BSM): WATCH THIS SPACE.